

THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Human-Machine Interface Considerations for Design and Testing
in Distributed Sociotechnical Systems

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ABSTRACT

The increasing concerns for safety and environmental sustainability create demands on the development of future maritime transportation strategies. One way to meet these demands is the concept of autonomous unmanned vessels for intercontinental voyages. As automation is being introduced onboard and watch keeping operations being migrated to the shore, there is a risk introducing *new* human factor issues among the various stakeholder groups and add to the complexity of the actors' roles. This licentiate was based on the context of an EU research project MUNIN (Maritime Unmanned Ship through Intelligence in Networks) about remote monitoring and controlling autonomous unmanned ships where the bridge and engine control room were moved from the ship to a land based control station.

Human Machine Interface, as a mediating artefact in the complex system to bridge automation/engine control is of importance for situation awareness, reliability, efficiency, effectiveness, resilience and safety. The purpose of the thesis is to achieve a comprehensive understanding of the complexity of Human Machine Interface in a distributed complex system by exploring the experiences of the human agents during the designing and testing phases of a designed for purpose Human Machine Interface.

The results reveal prominent human factor issues related to situation awareness and automation bias within such a complex distributed sociotechnical system, which sheds light on the design considerations of Human Machine Interface. Loss of presence can lead to critical perceptual bottlenecks which could negatively impact upon the operators; the organizational factors also greatly shape individual and team performance. It indicates that the contextual factors in the distributed sociotechnical system must be accommodated by the interface design through a holistic systemic approach. The Human Machine Interface shall not only support data visualization, but also the process and context in which data are utilized and understood for consensus decision-making.

Keywords: Human Factors, Design, Human Machine Interface, Situation Awareness, Automation Bias, Distributed Sociotechnical System, Decision Making, Maritime Transportation

APPENDED ARTICLES

This thesis is based on the work contained in the following articles:

ARTICLES I

Man, Y., Lundh, M., & Porathe, T. (2014). *Seeking harmony in shore-based unmanned ship handling – From the perspective of human factors, what is the difference we need to focus on from being onboard to onshore?* Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics (AHFE 2014) and the Affiliated Conferences, Krakow, Poland.

ARTICLES II

Man, Y., Lundh, M., Porathe, T., & MacKinnon, S. (2015). *From Desk To Field - Human Factor Issues In Remote Monitoring and Controlling of Autonomous Unmanned Vessels. Procedia Manufacturing, Volume 3, Pages 2674-2681.* Paper presented at the 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, Las Vegas, USA.

ARTICLES III

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TO SHORE FOR SHIP-HANDLING 28

LIST OF ABBREVIATIONS

ACM	Association for Computing Machinery
AT	Activity Theory
BIMCO	Baltic and International Maritime Council
CCTV	Closed-Circuit Television
COLREGs	International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
CWA	Cognitive Work Analysis
DMI	Direct Manipulation Interfaces
ECDIS	Electronic Chart Display and Information System
EID	Ecological Interface Design
GHG	Green House Gas
GPS	Global Positioning System
GUI	Graphical User Interface
HAS	Human Automation System
HCI	Human Computer Interaction
HMC	Human Machine Cooperation
HMI	Human Machine Interface
HMS	Human Machine System
ISF	International Shipping Federation
IMO	International Maritime Organization
IoT	Internet of Things

IPCC	Intergovernmental Panel on Climate Change
JCS	Joint Cognitive System
MUNIN	Maritime Unmanned Ship through Intelligence in Networks
QIUSS	Quality In Use Scoring Scale
SA	Situation Awareness
SD	Standard Deviation
SART	Situation Awareness Rating Technique
SCC	Shore-based Control Centre
SIGCHI	Special Interest Group on Computer Human Interaction
SIGSOC	Special Interest Group on Social and Behavioural Computing
SOCA	Social Organization and Cooperation Analyses
TCPA	Time to Closest Point of Approach
USV	Unmanned Surface Vessels
WCA	Worker Competencies Analysis

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*“Good design is in all the things you notice.
Great design is in all the things you don’t. ”*

— Wim Hovens

1 Introduction

Historically merchant shipping has been an important aspect of the world economy and as globalisation of the marketplace continues to grow so will be the importance of maritime transportation. Today roughly ninety percent of the world trade is carried by sea with over seventy percent as containerized cargo (Castonguay, 2009). Interconnecting more modern international transport systems such as roads, railways, shipping lines and air freight service, deep-sea shipping is the only economic transport between the continental landmasses for high-volume inter-regional cargoes, with its high-traffic major routes distributed between the industrial regions of Asia, Europe and North America (Stopford, 2009).

Confronted with heavy reliance of international maritime transportation for regional development, the merchant shipping industry has to deal with the challenges in growth and transport sustainability demands. One of the biggest challenges facing the entire shipping industry is environmental concerns over the effects of increased sea traffic. The third International Maritime Organization (IMO) Green House Gas (GHG) Study 2014 has revealed that for the period 2007–2012, on average, shipping accounted for approximately 3.1% of annual global CO₂ and approximately 2.8% of annual GHGs on a CO₂ emission basis using 100-year global warming potential conversions from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IMO, 2014). In fact, shipping was the last mode of transport for which GHG emissions were not regulated until July, 2011 (Psaraftis, 2012).

In addition to the environmental standpoints, safety as well as social and economic concerns regarding sustainability have become the vital cornerstones for the development of future maritime transportation strategy. Intensive scrutiny of seafarers' working environment have revealed that this unique profession of shift-based seafaring, which was described as "the original 24 hours society" (Filor, 1996), or "to be a part of a crew is to be a part of an isolated context" (Aubert, 1968; Eldh, 2004; Lundh, 2010). It involves work in one restricted location for a significant period of time without a break, working 24/7 in a potentially stressful and dangerous environment (Håvold, 2015). In an enclosed space the ship crew has to conduct demanding physical and cognitive activities (Mallam, 2014) and deal with problems in difficult situations when a ship is in distress and life of those onboard are threatened (Lundh, 2010). Work pressure, fatigue, environmental factors and long periods of time away from home contribute to these high work stresses (Hetherington, Flin, & Mearns, 2006). In a way the work demands shapes the maritime industry from other industries as much more stress and pressure from seafarers has been reported than other work group work (Parker, Hubinger, Green, Sargent, & Boyd, 2002). High degrees of fatigue and stress reduce awareness, productivity and lead to higher risk of making mistakes (Håvold, 2015; Trakada, Chrousos, Pejovic, & Vgontzas, 2007). According to a study from (Phillips, 2000), thirty nine percent of Incident at Sea Reports describe sleeping and sleepiness (fatigue) as contributory to an accident. Allen,

Wadsworth, and Smith (2008) found that there are quite a few factors commonly associated with the high incidence of fatigue, such as irregular circadian rhythms, long time working shift, continuous noise and motion, insufficient restorative sleep as well as the shortage of personnel for watchkeeping.

What makes the situation paradoxically worse is that more advanced navigational technologies been introduced onto the bridge. Accidents, like the grounding of the *Royal Majesty* due to the lack of proper feedback when the Global Positioning System (GPS) signal was lost, suggested that the deployment and utilization of poorly designed automation may not put human element into a centre place (Lützhöft & Dekker, 2002). With the trend to automate navigational functions onboard, decisions are more frequently suggested and even handled by automated aids, which might cause complacency and bias in human use of automation. Lack of equipment standardization and usability exacerbates the complexities and poses more pressure and stress on fatigable deck officers, which in return lead to a high incidence of maritime accidents (Grech, 2008). From 2000 - 2005, an average of 18 ships collided, grounded, sank, caught fire or exploded every single day while incredibly, two ships sank every day (Shanahan, 2010). In many accidents, reports concluded that “human error” and “not enough training” as the causes of system failure and end of the investigations (Lützhöft & Dekker, 2002; Sanquist, 1992; Shanahan, 2010; Woods, Dekker, Cook, Johannesen, & Sarter, 2010) instead of discovering the systemic aspect of the organizational complexities - connections between human error and characteristics of people, tools and task environment.

Maritime safety stands in the centre of these vocational challenges. Deep-sea seafaring is usually characterized as a repetitive work filled with routine and monotonous tasks for a longer time in open water with much less dense traffic but unpredictable weather. It certainly poses even more significant challenges to future transport sustainability. From the perspective of personal needs, the ship’s crew have to undergo more stress in ship-handling at critical moments (Prison, 2013) and have no choice but suffer long-time fatigue. All these factors make the working conditions onboard much less attractive today, which is likely to discourage young people to enter the maritime professions. In a comprehensive study report of the worldwide supply and demand for seafarers by the Baltic and International Maritime Council (BIMCO) and the International Shipping Federation (ISF), it was reported that “the industry will most probably face a tightening labour market...unless measures are taken to ensure a continued rapid growth in qualified seafarer numbers” (Lang, 2010). In the long run, it will probably drive the global downward trend to reduce onboard human labour for cost reduction (Grech, 2008).

1.1 Development of Autonomous Unmanned Vessels and Shore-based Operations

The less-than-desirable human work environment and reduced crew numbers together with the demand from environment concerns bring about the blossom of higher-level

automation and challenging ideas of unmanned vessels. A rationale behind the development of autonomous unmanned vessels for intercontinental voyages is the reduction of CO₂ emissions associated with slow steaming. By reducing the speed of a typical container vessel by 30%, a 50% reduction in fuel consumption and GHG emissions can be achieved (Cariou, 2011). With lowered speeds and the open sailing environments during deep-sea voyages, it may be feasible to replace the human operator with automation technologies specific to watchkeeping and engineering. Besides assumedly worse working environment with manned condition as a result of slow steaming (e.g. longer time of voyages) also prompts the trend to move the people from ship to shore and involve them in tasks like remote supervisory control to maintain unmanned ship safety. Considering safety is of paramount importance for deep-sea seafaring, it is expected that some safety benefit may be gained by moving bridge officers from the “24 hours society” where stress and fatigue permeate and dominate in their long-time tasks and work, to a shore-based office environment with 8 hours working shift scheme and elaborately designed decision-making support system.

Full or semi autonomously controlled systems are not rare in other transportation areas. Research about unmanned aerial systems (Hobbs, 2010; Kurkcu, Erhan, & Umut, 2012; A. C. Trujillo et al., 2015; Vincenzi, Terwilliger, & Ison, 2015) has occurred in the aviation domain, while in road transport sectors driverless metros in Kuala Lumpur, Dubai, Tokyo and Copenhagen featured with obstacle detection and extensive Closed-Circuit Televisions (CCTVs) links to a control centre have become the reality. Research and development into unmanned surface vessels for military applications has been ongoing for years, yet the conceptual applications for deep-sea shipping remain relatively unexplored.

The prevalence of autonomous applications in other industries has prompted the shipping industry to start to explore the similar applications, such as unmanned underwater vehicles (Ho, Pavlovic, & Arrabito, 2011) and Unmanned Surface Vessels (USV) (Osga et al., 2013; Osga & McWilliams, 2015). The development of unmanned cargo ships for regional shipping (such as the Baltic Sea) has just started in this \$375 billion shipping industry. Rolls-Royce set up a virtual reality prototype for unmanned cargo ships in 2014 (Bloomberg, 2014) and announced a new collaborative research project on unmanned ships with supervisory shore-based control station in August 2015 (Aplin, 2015). In 2012 a three year EU 7th Framework Project called MUNIN (Maritime Unmanned Ship through Intelligence in Networks) was launched to examine the feasibility of autonomous unmanned cargo vessels and their human centred automation governance from a Shore-based Control Centre (SCC). In MUNIN, a simulated 200 m long dry bulk carrier is mostly autonomously controlled with elaborately designed artificial intelligence although constantly monitored by a SCC operator. IMO’s e-Navigation project shares the same need of enhancing safety of navigation as the MUNIN project, and its scope also covers the coordination and cooperation between ship and shore (Burmeister, Bruhn, Rødseth, & Porathe, 2014).

With more operations migrated to the shore side, the challenges in shipping are gradually shifting to the design and development of automated systems. The introduction of automation not only aims to handle routine manual tasks, but also provide automated decision aid to human operator to cope with complexities in the field. Human Machine Interface (HMI) is an *ad hoc* artefact in the system that bridges the world of automation and mind of awareness. One classic research pillar in HMI is concerning on the mechanism of information perception and data visualization, such as the use Gestalt Laws of Perception to design better user interface to help the operators to perceive information (O'Connor, 2015). With higher levels of automation technology, the emergence of cloud computing service, a flatter form of a shipping organization, and decentralized decision making processes, the research on HMI considers a paradigm shift. In a highly automated system, Human Machine Interaction is turning into Human Machine Cooperation (Hoc, 2000). It might be important to gain insights from experiences of the human agents for designing a reliable HMI in a system, as a new approach to design for supporting decision-making and problem solving. For this purpose, a HMI prototype was developed by the MUNIN project team to support an SCC operator to remote monitor and control six unmanned vessels (see Figure 1). It is comprised of six dashboards (one per vessel, top and bottom middle), a customized electronic sea chart (bottom left), and a conning display (bottom right) and a weather chart (top right). During most of an intercontinental voyage, ships are autonomously controlled by their on-board computerized system and regularly send information to the SCC operator for monitoring purposes. One operator can check the overall status of all six vessels, as well as, categorized and monitor information from each vessel by cycling through each of the six dashboards.



Figure 1. The supervisory system developed for remote monitor and control

On the top “layer” of each dashboard there are nine information panels an operator can explore to discover more specific information about a control process (see Figure 2). Each information panel in the dashboard has a colour flag as the top flag: Green, Yellow or Red. If everything is operating normally or there is no impending threat, then all nine top flags in the dashboards shall show green flags. If some values on a ship diverge from the

pre-set threshold and the autonomous ship controller is incapable of correcting, the system will call for help by sending either Yellow or Red flag to the SCC to alert the operator of an abnormality. Yellow stands for a non-critical situation that might not require immediate intervention but only the operator's attention. A Red Flag on the dashboard stands for a critical situation within a certain operational category. For instance, in Figure 2, the top-layer category panel "Sailing" indicates a Red Flag, which requires the operator to investigate through deeper information layers and take corrective actions immediately. Typically the onboard autonomous ship controller controls the unmanned vessel as per a pre-voyage plan. Besides, a modes viewer has been designed in the top-layer user interface to display which modes of the automation. It include autonomous (autonomous execution where the ship follows a predefined track and speed plus autonomous control where she could automatically manoeuvre for collision avoidance or re-route due to weather conditions), remote control where the ship was completely under the command of the SCC, fail-to-safe and manual onboard control.

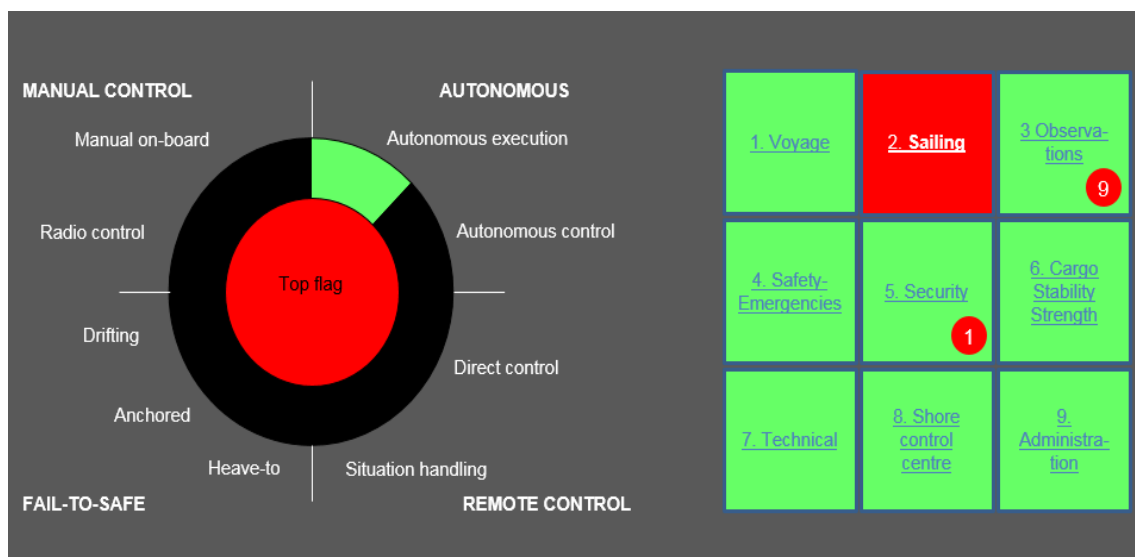


Figure 2. One dashboard can display nine groups of information from one unmanned ship

While this HMI design seems to be concise and clear, the challenging concept of moving a ship bridge to a SCC itself could deprive the operators of important contextual information gained at sea. Would this lead to unprecedented gaps in the decision-making process? If so, how a HMI design may anticipate these issues and furthermore support the shore-based operator could become a cross-disciplinary question beyond software engineering or user interface programming. For instance, the effect of geographically remote located automation (i.e. distributed properties of a system) on the performance of operators might be indispensable considerations within the design of a robust and reliable HMI for decision making support.

1.2 Human Factors Pertinent to Automated Decision Support System

The 21 km unmanned metro in Copenhagen was characterised as the “safety strengthener” and “remover of human error” by the Copenhagen Metro chief executive Piero Marotta (Fischer, 2011). While automation has great advantages for quality control and performance efficiency in handling routine tasks, with its programming limitations, automation will, inevitably create new emerging paths for unexpected kinds of human errors, generally referred to as the “ironies of automation” (Bainbridge, 1983). Studies on automation bias and the association between human errors/decision making and highly automated decision environments are becoming more common (Mosier, Skitka, Dunbar, & McDonnell, 2001; Skitka, Mosier, & Burdick, 1999, 2000). Automation may also create both physical isolation and mental isolation (“out-of-loop”) for operators (Norman, 1990). Human error, as an outcome of automation is primarily due to ill design of HMI - which is traditionally technology-driven and demands the human operator to adapt to the machines. HMI is considered as one of the principal parts of social-technical systems and must be considered when developing a newly complex automation system. It needs to address human limitation and capabilities and provide efficient, effective and most importantly, safety support.

Striving for safety could definitely be one core driving factors for the development of unmanned, autonomous merchant cargo ships such as the case proposed in the MUNIN project. In such a safety-critical domain, the HMI research of interest is on the “integration of monitoring human operator and functioning complex automation and the management of the growing disparity between control and accountability in automated systems” (Grote, Weyer, & Stanton, 2014, p. 289). These are the essential prerequisites of the success of a decision support application in a highly automated system context. Without careful and thorough examination on these issues regarding HMI design, the eventual deployment of automated technologies could paradoxically lead to accidents.

From a traditional view of Human Computer Interaction (HCI), interfaces can be seen as a vital representational tool that the operator uses to “see” the world and make sense of the situation. Interfaces also provide the affordance for operators to behave and take actions. The successful design of human machine interface design highly depends on the specific task demands, characteristics of the work domain and constraints in the context. For example in the MUNIN project, the constraints relevant to the fact that operators working in a shore control centre with contrast to working on a bridge or in an engine room would hugely influence the HMI design as shore-based operators probably may not react important cues that are available to onboard crew (i.e. motion environments). How to map the “invisible world” from the complex filed to the interface to truly enhance the operator’s capability to understand the situation instead of overloading them is of paramount importance in nearly all decision support systems.

Insights into human cognition can also be gained through the exploration of HMI, e.g. the relationship between performance and structure of the representation (Bennett & Flach, 2011, p. xix). While many condemn automation or high-level automation as the culprit of accidents, Norman (1990) argued that the problem is not automation but the feedback provided by the interfaces, which combined with the system complexity can greatly jeopardize operators' Situation Awareness (SA). For example in the MUNIN project, when an operator was located in an office-like environment to conduct remote supervisory control instead of being situated on a bridge, the capability of a HMI to provide appropriate feedback as a mean of filling the gap of contextual information deprivation is vital for the operator to maintain SA. The loss of SA leads to higher incidence of human error (Grech, 2008) and was considered as the primary causal factor in many accidents, especially within a highly automated system context (Endsley, 2011; Grech, Horberry, & Smith, 2002). Other factors can influence SA as well, such as operator's workload and mental models, which are also the key elements to consider when optimizing and employing new technologies for decision support and problem solving.

1.3 Research Aims and Themes Explored

The primary goal is to achieve a deeper understanding of the complexity of HMI by exploring the factors associated within the HMI, in order to generate system design knowledge to improve the operator's SA and overall system performance. This thesis is to address prominent human factor issues related to SA and decision making within a complex sociotechnical system by using the MUNIN experiences of remote supervisory control operations towards unmanned autonomous vessels. It also aims to reveal the underpinnings of a reliable decision support HMI by investigating how the distributed properties of the system could influence the system performance. These insights and knowledge should contribute to a better understanding towards the constructs of ecological interface design and sociotechnical system design.

Experiences from the MUNIN project provides a contextual background to the general research questions about how to facilitate human element concerns in a highly automated system for information processing and problem solving. An unmanned ship does not mean that the problems associated with human error will disappear. Realistically, the centralized organization typical of a manned bridge and engine room would become a decentralized sociotechnical system, monitored or controlled by shore-based operators. Thus the opportunity for human error is not reduced or eliminated, but manifest itself in other ways; situations not yet fully understood by human factor specialists. The research on the remote governance of autonomous unmanned vessels intends to uncover these unexplored dimensions through understanding how human element would be affected and how the information technology could assist human agents coping with complexity of the system. As sociotechnical systems become less centralized and more globalized, it creates more opportunities for further human factors research.

1.3.1 Research Questions

The research questions guiding the licentiate thesis are:

- What are the barriers to adequate situation awareness and decision making within an automated decision support system for supervisory operations?
- How can HMI concepts address human factors issues such as individual and team situation awareness, supervisory control of highly automated systems, and improvement of information transparency in complex sociotechnical systems?
- How can HMI concepts be developed to derive reliable automated decision support systems that can accommodate the demands of a Human-Automation System in both distributed and/or centralized contexts?
- How can HMI concepts be evolved and adapted to the increasing system time constraints, variability, uncertainty and complexities?

1.3.2 Appended Articles

The appended articles in this licentiate thesis are:

Article I: Man, Y., Lundh, M., & Porathe, T. (2014). *Seeking harmony in shore-based unmanned ship handling – From the perspective of human factors, what is the difference we need to focus on from being onboard to onshore?* Paper presented at the 5th International Conference on Applied Human Factors and Ergonomics (AHFE 2014) and the Affiliated Conferences, Krakow, Poland.

While the notions of ship sense and harmony are originally created for onboard ship manoeuvring, this paper extends it to the domain of shore-based control centres for unmanned ship handling. Master mariner students participated in a focus group to discuss how different actions taken onboard and likely to be taken onshore. The aim is to explore the underlying shifted human factors and identify those vital aspects in information processing that should be well considered in an early stage of design for a shore-based control centre.

Article II: Man, Y., Lundh, M., Porathe, T., & MacKinnon, S. (2015). *From Desk To Field - Human Factor Issues In Remote Monitoring and Controlling of Autonomous Unmanned Vessels*. *Procedia Manufacturing*, Volume 3, Pages 2674-2681. <http://dx.doi.org/10.1016/j.promfg.2015.07.635>. Paper presented at the 6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015, Las Vegas.

Previous research suggests maintaining adequate situation awareness as a primary challenge related to human-centre automation. The purpose of this study was to identify the human factor issues in remote monitoring and controlling of autonomous unmanned vessels through a scenario-based quasi-experiment by four master mariners and a ship engineer. The literature review and fieldwork data identified gaps in the in the shore-based monitoring context, suggesting aspects on which the design could be improved to support operator's situation awareness and decision making to regain harmony remotely.

Article III: MacKinnon, S., Man, Y., Lundh, M., & Porathe, T. (2015). *Command and Control of Unmanned Vessels: Keep Shore Based Operators In-The-Loop*. Paper presented at the NAV 2015 18th International Conference on Ships and Shipping Research, Milan, Italy.

Conventional thinking suggests that we augment operator decision making with artificially intelligent support systems. Whether these technologies keep the operator “in-the-loop” or diminish overall situation awareness remains to be seen and are dependent upon the quality and robustness of the HMI to monitor and control the automation systems. A sudden failure of a highly complex system, whose “artificial intelligence” is not transparent to the operator, may prove beyond the cognitive means of a highly stressed operator to troubleshoot the situation and recover on time. This paper examines the state of individual SA and team SA in monitoring several vessels as part of a Shore-based Control Centre, the hub of an autonomous, unmanned vessel concept.

1.4 Delimitations

The taxonomy of HMI can be very broad. In this thesis it may only refer to the most typical automated decision support system interfaces (e.g. display and so on) for the operator to conduct supervisory tasks. This thesis does neither intend to put considerable emphasis on interface technologies such as window forms or menus, nor generate the best practice guidelines of HMI design for practitioners. The focus is to attempt to build overarching theoretical synthesis of SA, ecology, uncertainties, complexity and other pertinent human factors to comprehend the benefits of a HMI system with proper design. This approach should further elucidate the nature of HMI concept and to probe barriers / constituents related to robustness and reliability of a decision support HMI in a highly automated environment. The should shed light upon the successful integration of human and automation in an increasingly automated system as well as both theoretical and practical designing thoughts for complex sociotechnical systems.

The research work related to the MUNIN project is woven into my journey of HMI design and discussion. The concept of the MUNIN project includes the feasibility study of designing a decision support HMI for the *ad hoc* shore-based information system. But it is not the purpose of HMI discussion covered in this thesis, although it may be referred to for contextual purposes. What is important is that the project provides the detailed context for us to research about the general human factors pertinent to a decision support HMI design in a distributed work domain. Certain engineering-oriented implementation is based on the current assumptions made in the MUNIN project and the generation of knowledge is partly based on the observed phenomena in the field. Despite the limitations brought by such contextual scenarios and applications, it is still promising to gain the insights about usable and decision support HMI in general. Nevertheless, the HMI example in this thesis may not be necessarily the general decision support tool for all kinds of situations regarding shore-based management for autonomous unmanned ships in the future.

2 Theoretical Framework and Related Research

This chapter provides a theoretical context for which the studies and theoretical inferences presented later in the licentiate thesis can be understood. Starting from the historical view on HMI research development, this chapter presents a theoretical context (human-automation system) progressing towards a closer examination of human performance and the holistic systemic factors (situation awareness and socio-technical systems).

2.1 Human Machine Interaction as Interdisciplinary Research

A relatively simple and straight-forward definition of Human Machine Interaction can be given as “the interaction and communication between human users and a machine, a dynamic technical system, via a Human Machine Interface (HMI)” (Johannsen, 2007, p. 132). The concept of HMI has deep roots back to the first time a human interacted with a device to make sense of its surroundings, say for example, a compass. Human Machine Interaction was recognized as a scientific discipline when the International Journal of Man Machine Studies was first published in 1969 (Hollnagel, 2011). Coincidentally in the same year, the Association for Computing Machinery (ACM)’s Special Interest Group on Social and Behavioural Computing (SIGSOC) was formed to conduct both the social and behavioural sciences with computers, which was the predecessor of ACM Special Interest Group on Computer-Human Interaction (SIGCHI) (Borman, 1996). With the first ACM SIGCHI conference on human factors in computing systems being held in 1983 and the arrival of the legendary the Apple Macintosh in 1984, Human Computer Interaction (HCI) was recognized as a specific research domain within the discipline of Human Machine Interaction (MacKenzie, 2012). As Microsoft Windows emerged in the mid-80s and Graphical User Interface (GUI) software became the computing norm, HCI research grew significantly in 90s and became what is known today as the field of Human Machine Interaction. With the stunning speed of technology research and development, mobile and wearable digital devices (e.g. smartphones, smartwatches) are literally becoming ubiquitous (Man & Ngai, 2014), so is Human Machine (Computer) Interaction. The advent of the era of “Internet of Things (IoT)” suggests that as the numbers of machine we will interact is going to grow considerably, so will be the automation level and the complexity of interaction with these digital devices.

2.1.1 HMI Research from Information Processing to Cognitive System Engineering Perspectives

Over the past decades, the goal of Human Machine Interaction research remains consistent – striving for an efficient, effective, safe accomplishment of a task (Hollnagel, 2011) in a Human Machine System (HMS). HMS is a system composed of human users, machines, and the HMI. The HMI, usually in a tangible form as visualized software, serves as the key coupling between two principle components (user and machine).

Building upon Skinner's Stimulus-Response Theory as a view of the information process, the human's cognitive system perceptually process the Stimulus(S) from the interface and then makes a Response (R) to the interface after reasoning and decision making (Bellet, 2011) (see Figure 3). This model can be seen as a monadic linear model because it indicates a linear process to reflect the order and meaning of the world by a user's mind as the only cognitive substance.



Figure 3. Adapted S-R model to represent human information processing

The Rasmussen (1987) model perhaps better explains the operator's information processing from Skill-Rules-Knowledge three levels grounded on the control theory (see Figure 4).

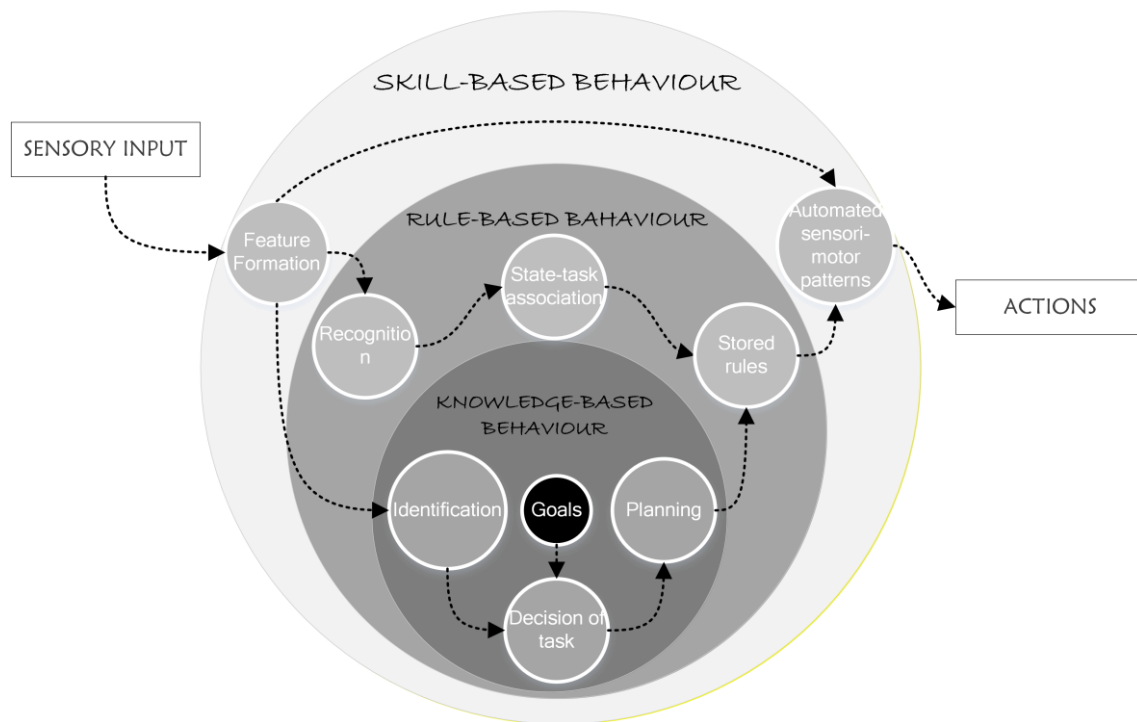


Figure 4. Adapted Rasmussen (1987) model on three levels of performance of skilled human operators

In a conventional dyadic modelling of Human and Machine, the user is constantly sending control command to the interface and receiving feedback via the perceptual sensors in a closed information processing loop (Åström & Murray, 2008). In this view (see Figure 5), the HMI is the connecting bridge of human cognition (transferring intention into performance and action) and engineering processing (executing programmed procedures). The ill-designed Human Machine Interface could easily cause the difficulties during Human Machine Interaction when the user performs the tasks. Norman

(2013) defines these difficulties as “the Gulf of Execution” and “the Gulf of Evaluation” in his action cycle model, which respectively reflect “the difference between what the user wants to do and what can actually be done using controls that are available”, and “the mismatch between the user’s intention and expectation and the actual state of the system” (Faulkner, 2000, p. 81).

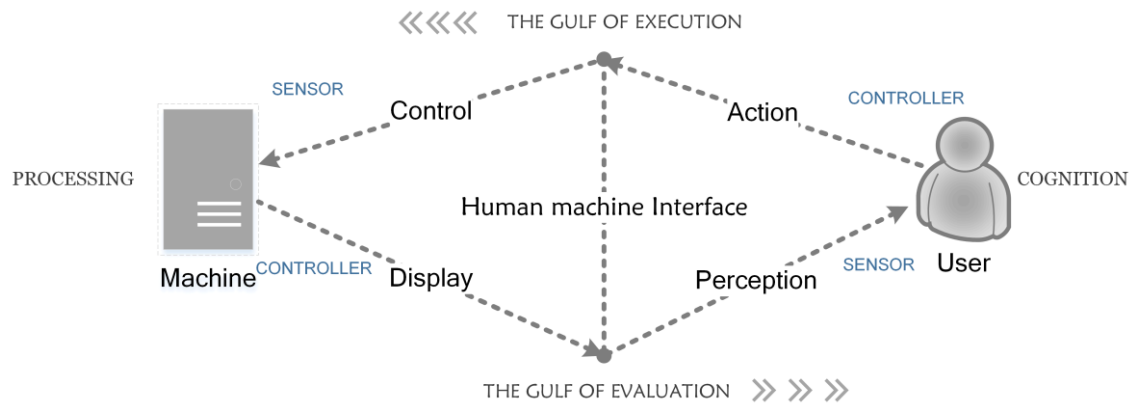


Figure 5. An action cycle model to present the two gulfs

The classic two gulfs revealed the tight coupling nature of HMI design and human cognition for information processing. It prompted HMI research to be typically an interdisciplinary research area with a huge contribution from the cognitive engineering domain - “it is a type of applied cognitive science, trying to apply what is known from science to the design and construction of machines” (Norman, 1983, p. 31). The focus of HMI was not only about the human performance, about supporting attention or perception for human operators, but more importantly, was to buttress the operator’s understanding of the situation in the work environment (Rasmussen, 1986, 1987). Since then cognitive science and ergonomics opened the doors for research of HMI regarding system complexity to a broader discussion about the integration of human-technology within a context - cognitive system engineering and joint cognitive system (Hollnagel & Woods, 1999, 2005; Mancini, Woods, & Hollnagel, 1988; Woods & Hollnagel, 2006), situation awareness (Endsley, 1988, 1995a, 1995b, 2011, 2015a, 2015b; Endsley & Jones, 2001), distributed situation awareness (Salmon, Stanton, Walker, & Jenkins, 2009; Stanton, 2013; Stanton, Salmon, & Walker, 2015; Stanton, Salmon, Walker, & Jenkins, 2009), distributed cognition (Hutchins, 1995), the ecological nature of HMI and Ecological Interface Design (EID) (Bennett & Flach, 2011; Flach, Hancock, Caird, & Vicente, 1995; Gibson, 2014; Vicente, 2002; Vicente & Rasmussen, 1992), with the key focus on human-technology-environment and treatment of cognition as a function that is distributed over an agent and its ecology (Flach, 2015) (see Figure 6).

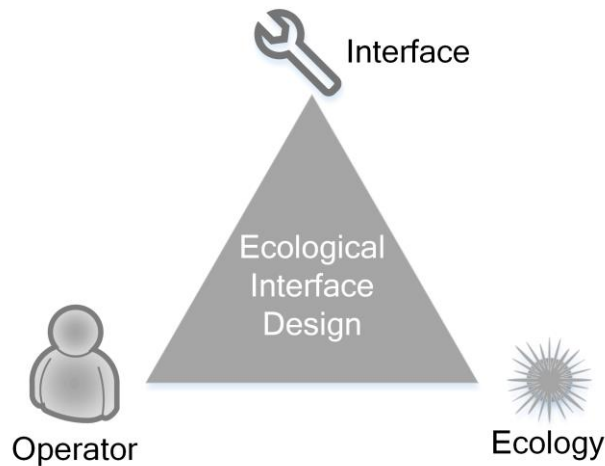


Figure 6. Adapted triadic semiotic model from the ecological perspective

With the paradigm shift (Kuhn, 1962) in the research area of HMS, more from cognitive psychology or interface technology to ecology, the HMI design today gets highly associated with the comprehensive task analysis which aims to obtain a global understanding of the system's boundaries, functionality, and variability etc. Twenty years ago it might not need such analysis for a text processing software used in office which the HMS is loosely coupled to the environment with less performance variability, but for complex systems used in nuclear plant, cockpit and ship bridge that are “underspecified or intractable, it is clearly not possible to prescribe tasks and actions in detail, hence to design the HMI in detail” (Hollnagel, 2011, p. 423). Resilient systems which can absorb the disturbing factors rather than designing exact HMI has been discussed by Hollnagel, Woods, and Leveson (2006). Versatile cognitive task analysis methods have been proposed and receiving increasing concern for the past decade (Diaper & Stanton, 2003; Hollnagel, 2003; Schraagen, Chipman, & Shalin, 2000; Stanton, 2006; Stanton, Salmon, Walker, Baber, & Jenkins, 2006).

2.1.2 Activity Theory in HMI

Prevailing cognitive approaches have been criticised for their “limitation to provide an appropriate conceptual basis for studies of computer use in its social, organizational and cultural context” (Kaptelinin, 1996). The research in Activity Theory (AT) pioneered by Vygotsky (1934) therefore has an important impact on the research of HMI, with the notion of using AT as a representational reflection framework for HCI (Andersson, Bligård, Osvalder, Rissanen, & Tripathi, 2011; Kuutti, 1995). HMI is considered as a mediating tool between a human operator and an object in the context (see Figure 7). Through the lens of AT, the design of any artefact (including HMI) need to involve the design of individual or organizational human activity (Kaptelinin, 1996) and understanding the context as a whole. This implies that applying AT in HCI is not only an attempt to reflect how HMI could be designed regarding various levels of activity, actions and operations, but importantly to provide an approach to study how the individual use of the tool can influence the others in the organization (Kaptelinin, 1996; Kuutti, 1995).

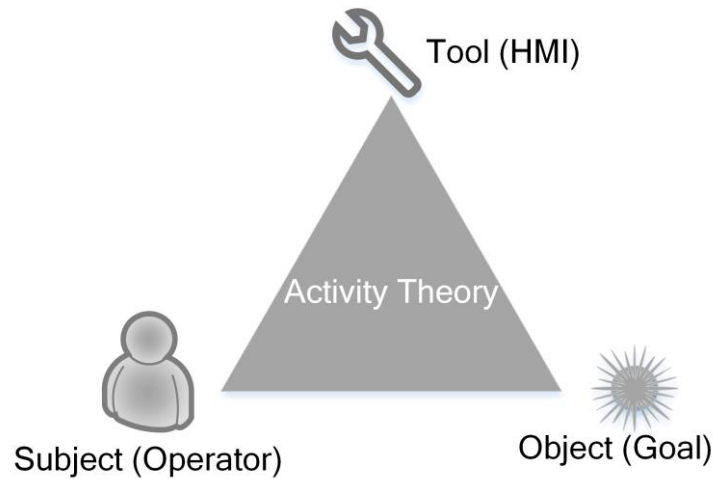


Figure 7. The mediated relationship at operator's level

2.2 Human Automation System and Supervisory Control

With the increasing importance on effectiveness, efficiency and safety in various automation-dominant industries, another central research issue in Human Machine System concerns the coupling of humans and automations in a Human-Automation System (HAS) (Sheridan, 2002). Automation was developed to overcome the limitations of humans in complex contexts for various tasks. The higher degree of the automation, more complex and sophisticated control structure and process will become (Johannsen, 1992, 2007). Along with the expected efficiency for complex tasks in nuclear power plant, ship bridge and airplane cockpit, human errors were ironically prevalent in accidents (Bainbridge, 1983; Woods et al., 2010), usually the type of ones that a user could hardly make when using a desktop text processing system to write an article. Human errors were often evoked in the absence of technological explanations (Stanton, 2003) and two approaches were usually to view the problem of human fallibility (Reason, 2000) – the personal approach discussed about the individual problems such as inattention and memory lapse while the system approach focused on the work conditions for individuals, such as over-automation and automation bias (Hancock, 2013; Mosier et al., 2001; Norman, 1990; Skitka et al., 1999, 2000). Here we take a system approach to view the control structure in HAS and its implication for human error.

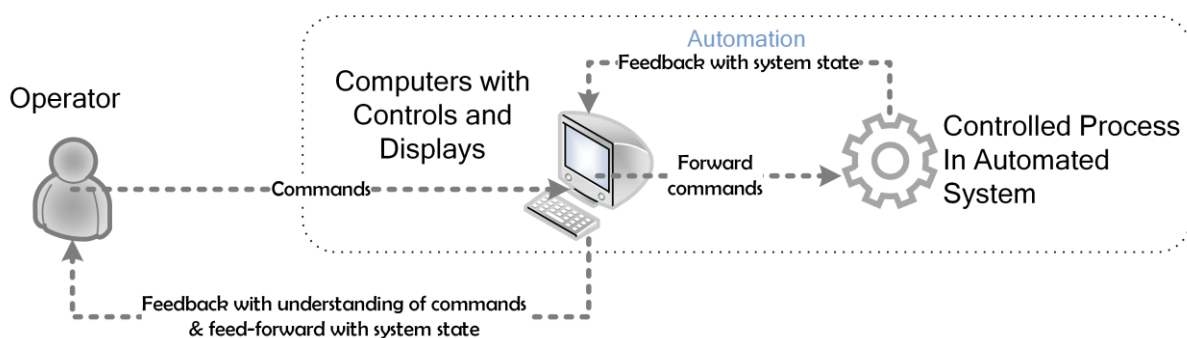


Figure 8. An operator receives the feedback in Supervisory Control of HAS

One prominent change in the HAS over the past years is the shifting role of the operator (Boy, 2011; Johannsen, 2007; Sheridan, 1992): While the machines are getting increasingly automated and “intelligent”, they are designed to attempt to take accountability in rule and even knowledge-based level of Rasmussen (1987)’s Skill-Rules-Knowledge Behaviour Model. Conventional Human Machine Interaction is changing to Human Machine Cooperation (Hoc, 2000) with the operator’s role progressively shifting from a controller to a mission manager or supervisor of the cognitive system (Trujillo, Fan, & Hempley, 2015). The emerging supervisory form of control by the operator over the automation system is therefore inherent in HAS, which is defined in a general level as “human operators are intermittently programming and receiving information from a computer that interconnects through artificial sensors and effectors to the controlled process or task environment” (Sheridan, 2002, p. 115). The feedback, “the most effective way to communicate information and guide the mental model” of the operator (Proctor & Vu, 2003, p. 33), was not limited to the information about the computer’s understanding of the operator’s commands from the proximal end, but interpreted feed-forward information by the computer, i.e. the state of the automated system at the distal end (see Figure 8). The automation here refers to the aggregation of the sensing of environmental variables, data processing combined with mechanical activities in the system, and automated decision aid. Supervisory control could be further complicated with more computers standing in between the operator and the controlled process. When the operator interacts with a computer to communicate with an *ad hoc* remote computer that actually controls the automatic process in the remote field, the system is in “remote supervisory control”; when more processes were involved to be controlled by the remote computer, the operator is in “remote multi-task supervisory control” (Sheridan, 2002).

Human supervision of automated systems essentially develops a new formality of coupling and communication between human and machines over the recent decades. The human operator is supposed to be planning the automatic procedures, programming the programmes, monitoring the automatic process, diagnosing problems and intervening in unanticipated situations, while learning from these experiences (Sheridan, 1992, 2002). A high degree of automation and extended functionalities are still incapable of handling unanticipated abnormal situations, which leaves the operator to remain the last barrier as a unique decision maker and problem solver in the system (Boy, 2011; Sheridan & Parasuraman, 2005). This brings huge risk to the overall safety and performance of the system (Bainbridge, 1983). The arising human factors issues were typically known as “physical isolation” (i.e. isolated from the physical structure of the airplane and ship) and “mental isolation” (i.e. isolated from the system state) by Norman (1990) – “automation tends to isolate the operator from the moment-to-moment technical operation details...when automatic fails, the crew’s relative isolation can dramatically increase the difficulties and the magnitude of the problem faced in diagnosing the situation...” (p. 3). In the case of onboard ship-handling, “ship-sense” (Prison, 2013; Prison, Dahlman, & Lundh, 2013; Prison, Lützhöft, & Porathe, 2009), is a “special feeling” used by the ship-handler to manoeuvre the vessel through the dynamic environment in a balanced manner. This could be considered as an important cognitive approach to engage operators actively in the environment to overcome the isolation effect for maintaining the “harmony” at sea. “Harmony” is defined by Prison

(2013) and is essentially the balancing act between the ship-handler's capabilities and task demands, consisting of *environmental prerequisites* (context and situation), *vessel specific prerequisites* (inertia and navigational instrument) and *personal prerequisites* (spatial awareness, theoretical knowledge and experience). However, in remote supervisory control, although state-of-the-art simulation technologies (e.g. Virtual Reality or Augmented Reality) could be utilized to mediate the operator's feeling of "presence" - "being there" (Barfield & Hendrix, 1995) in a virtual environment (MacKinnon, Evely, & Antle, 2009; Patterson, McCarter, MacKinnon, Veitch, & Simões Rê, 2011), there are many more factors that can influence the way in which an operator achieves "a perceptual illusion of non-mediation" (Lombard & Ditton, 1997; Witmer & Singer, 1998). Research on presence could contribute to unique problems caused by using mediating tools which were designed to tackle with the distributed properties of the remote supervisory control in a HAS, but has its limitation to resolve physical and mental isolation due to the intrinsic nature of supervisory control.

The concept of human-centre automation was to address the human factor issues regarding process control during the integration of high level of automation and human operators (Billings, 1997; Graeber & Billings, 1989; Oberheid, Hasselberg, & Söffker, 2011). Cognitive approaches were proposed to cope with human errors to achieve the overarching goal of safety and efficiency of the system (Hoc, 2001; Rasmussen & Vicente, 1989; Woods & Hollnagel, 2006), especially for the design of an expert system for control and diagnostics or knowledge-based decision support system (Roth, Bennett, & Woods, 1987). The contemporary research in HAS is essential concerned with integration of monitoring human operator and functioning complex automation and the management of the growing disparity between control and accountability in automated systems (Grote, Weyer, & Stanton, 2014).

2.3 Situation Awareness

Although it was asserted that automation can support good system performance in the absence of good Situation Awareness (SA) (Wickens, 2008), SA has drawn significant attention in parallel with automation in cognitive science for the past 25 years. There is extensive use and theoretical discussion of SA in maritime sectors, aviation industry, military training, teamwork, education and so on (Riley et al., 2008; Salmon et al., 2008; Wickens, 2008).

2.3.1 Individual Level

There are various definitions and explanations of SA terms and their orientation context (Chiappe, Strybel, & Vu, 2015; Durso & Sethumadhavan, 2008; Stanton et al., 2015). Endsley (1995b)'s SA model is one of most widely referenced SA models in Human Factors. It was defined as three levels of concept - "the perception of the elements in the environment within a volume of time and space (level 1 SA, perception), the comprehension of their meaning (level 2 SA, comprehension) and the projection of their status in the future (level 3 SA, projection/anticipation)", which was considered primarily applicable in dynamic situations by Wickens (2008).

However over the years, SA has also been criticised for being a “linear data-driven information processing model” (Salmon et al., 2008; Salmon, Stanton, & Young, 2011; Stanton et al., 2015; Stanton et al., 2009). Endsley has addressed that the SA model was a non-linear but cyclical model (“the three levels of SA represent ascending levels of SA not linear stages”) that was “beyond the traditional information approaches in attempting to explain human behavior in operating complex system” (Endsley, 2015a, 2015b). The argument was based that the important role of the mental model in directing attention to search the information - default values from the mental model can provide reasonable Level 1 SA values, so the operator does not necessarily have complete or accurate level 1 SA but can possess level 2 or 3 SA (Endsley, 2004). SA is not necessarily acquired instantaneously but is developed over time dynamically. Based on an operator’s mental model and dynamic situation, he is constantly “making meaningful integration of the disparate data taken in from the environment, as filtered through the relevant goals”, and using the situation model and goal to direct change in mental model. (Endsley, 2015b). “SA, decision making and action seems to be separate stages but they occur in loop acting on the environment, with the changing state of the environment in turn effecting those cognitive stages, often quite rapidly” (Endsley, 2015a). In terms of the “sense making”, it seems to be similar to the “Data Frame” model (i.e. using frames to define what counts as data and using data to select, maintain, construct frames) developed by Klein, Phillips, Rall, and Peluso (2007). Klein (2014) believed that “Data Frame” model is to “capture the strategies people use to makes sense of complex situations although there data elements are not clearly specified” but Endsley (1995b)’s SA is “a way to infuse cognitive psychology into human factors of designing systems that will help operators to handle limitations in working memory and attention”.

Endsley (1995b)’s SA model has also been criticized of being a “folk model” without empirical foundation and scientific status and only focus on cognition in the head - “information-processing model of human behaviour was wrong” (Dekker & Hollnagel, 2004). However Parasuraman, Sheridan, and Wickens (2008) argued that SA is a viable empirically supported cognitive engineering construct with the large science base of empirical studies on SA. Endsley (2015b) contended that SA is neither action or performance nor long term memory knowledge that only concerns what in the head. In the model of SA in dynamic decision making, there are *Individual Factors* (goals, objectives, expectations, information processing, longer term memory stores, automaticity) and *System Factors* (system capability, interface design, stress & workload, complexity and automation). “It is the situation specifics that determine the adoption of an appropriate mental model leading to the selection of problem solving strategies...the context matters a great deal for human decision making and provides a detailed discussion of the ways in which that occurs”(Endsley, 2015b). To better solve the problems regarding the constraints in the context, the goal-directed task analysis was developed to gain better SA and system performance as alternative to cognitive task analysis (Endsley, 2011). Some resent researches suggest that Endsley (1995b)’s SA model and ecological design do share much common ground (Endsley, 2015a; Flach, 2015; Minotra & Burns, 2015), aiming the same goal of supporting the operator’s decision making via designing complex sociotechnical systems.

2.3.2 Team Level Situation Awareness

Beside the intensive discussion on SA at the individual level, researches about how SA is formed and maintained in cooperative activities also draw huge concern in the past (Endsley, 2015b; Salmon et al., 2009; Sandhøland, Oltedal, Hystad, & Eid, 2015; Stanton et al., 2015; Stanton, Stewart, et al., 2006). “Team SA” was defined by Endsley (1995b) as “the degree to which every team member possess the SA needed for his or her job”. Another related term is “Shared SA”, “the degree to which team members have the same SA on shared SA requirements” (Endsley, 2011).

In the model of Team SA, there are devices that can be used by team members to form Team SA, such as communications, shared displays and shared environment (Endsley & Jones, 2001). The research on Team SA has rather important implication: new devices in workplaces should be carefully designed and examined to not to become the barriers of Team SA but really support each other's work.

In contrast with Endsley's Team SA and Shared SA, Stanton, Stewart, et al. (2006) proposed “Distributed SA”, which functions like, distributed cognition, being distributed in the world. It was asserted that the “distributed cognition perspective of situation awareness offers the most comprehensive explanation of the phenomena observed in socio-technical systems” (Stanton et al., 2009).

2.4 Sociotechnical Systems

A sociotechnical framework is a systematic approach to view human factors and dynamics in system performance (Grech, 2008). “The sociotechnical perspective is an effort to provide a model of how systems are larger than the sum of its parts” (Forsman, 2015). It provides a heuristic perspective to understand how systems are performing at a microscopic and macroscopic level by modelling the constituents and interactions.

One classic sociotechnical system framework is the “SHEL” sociotechnical system model, originally developed by Edwards (1972) and Hawkins (1993), which has significant impact on human factors principles and processes in aviation and maritime domain. The rationalization to put human (“Liveware”) in the centre for building the block model is that the human was rarely or the sole cause of an error or accident (Wiegmann & Shappell, 2003). In the “SHEL” model, the “Liveware” is the hub of the model of Human Factors so all the other peripheral components “Software” (e.g. navigational software programme), “Hardware” (e.g. mechanical machines), “Environment (e.g. sea state, weather)” and the other “Liveware” (e.g. people who also work on a bridge) must be adapted in a way that their interaction with the centred “Liveware” matches the characteristics of this central component (Hawkins, 1993).

However, the increasing difficulty of interpreting the model's component metaphors “H”, “S” and “E” became the barrier of its application, especially the hard distinction to be made between software and hardware as technology evolves (Grech, 2008). Nevertheless, the “SHEL” model

provided a holistic systematic approach for the research community to understand the human's characteristics and the relationship between environment and human operator. The focus was to discuss how design of the functionalities could support human-machine interaction and human-human interaction. One enlightened sociotechnical system model based on this is the "Septigon" model, which is *Society and Culture, Physical Environment, Practice, Technology, Individual, Group and Organizational Environment Network* (Koester, 2007). Still, these conventional models were criticized for separating the people, the technology, and the work into their own units of analysis and being limited in analysing factors, process and relationships that emerge at the intersections of people, technology and work in complex systems (Woods & Hollnagel, 2006). The analytical trends of sociotechnical systems regarding HMI design is shifting from overcoming individual limitations to supporting adaptability and maintaining control in the system – "Distributed SA" is developed to present a novel paradigm for explaining SA in sociotechnical systems (Stanton et al., 2015); Ecological design focuses on the impact of ecology on humans and model the triangle between human, technology and work domain (Bennett & Flach, 2011; Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992); Joint Cognitive System (JCS) is proposed to be the base unit of analysis to support design work to cope with complexity (Hollnagel & Woods, 1999, 2005; Woods & Hollnagel, 2006). In JCS, joint system performance is of paramount importance – "We should not be overly concerned with the performance of the pilot per se, but rather with the performance of the pilot + aircraft – in other words, the joint pilot aircraft system" (Dekker & Hollnagel, 2004, p. 85).

3 Methodological Framework

This licentiate concerns the human factors issues with regard to HMI design and their connections to the context. The work could get labeled as “applied” from this perspective and the results might be particular to the specific context in the laboratory environment. However, it is always the goal to seek those fundamental understandings beneath scientific problems and try to gain considerations on a broader scope as a basis for applications in the domain. This chapter not only presents the methodological tools chosen, but also explains the structure and paradigm in which the project work and theoretical elements are woven together.

3.1 Overall Approach and Research Paradigm

The research of supervisory control by decision support HMI is essentially concerned with understanding the constraints and barriers of the information processing in the human element in a new context characterized by distributed properties of the domain. A human operator usually acts as an offsite supervisor of a machine located in the field and develops individual SA through the interaction with the machine. Meanwhile the operator may interact with his teammates to develop the Team SA about the ongoing situation, which makes it a more complex sociotechnical system. During the design process of HMI, risk and instability may not only emerge from the perspective of the sharp end user’s needs, but also may be a consequence of inadequate analysis of organizational factors from a systemic level (Forsman, 2015; Vicente, 2006; Woods & Hollnagel, 2006). To uncover the actual human factor issues within a complex sociotechnical system such as the SCC in the MUNIN project, an alarm management system described in Chapter 1 was developed to support shore-based operators for supervisory control. The explorative testing about how a human operator remotely peeks and intervenes the world of automation through the prototype serves as the main approach to probe the research questions regarding a reliable decision support HMI in a distributed sociotechnical system. It could be considered as a reflective process to mirror the human factor challenges that are associated with the HMIs across multiple safety-critical domains (e.g. maritime, aviation or nuclear industry).

The essence of this research is to generate knowledge of the potential for HMI used in a highly automated environment, all the while considering the operator’s limitation and capacities (awareness), the task needs and constraints in the field (situation), and their relationship by investigating the overall social phenomena. The knowledge corresponding to the social reality can be demonstrated through the MUNIN context to shed light on the research questions. Systematizing the bridge situation onboard from the centralized sociotechnical system perspective serves as our starting point. It aims to elucidate what issues are pertinent to the HMI needs to be accommodated theoretically to the changes occurred in a highly automated distributed context [Article 1]; then evaluate how the HMI functions regarding SA and decision making in the field from the operator’s perspective as well as adaptability and resilience from the whole sociotechnical system’s perspective [Article 2, 3]; all these build a foundation to, not only generate a deeper understanding of complexities of HMI that why and partially how HMI should be weaving the elements of human operator’s awareness and ecological constraints in

order to support SA and decision making in a distributed system, but also provide further opportunities to study and discuss how HMI concepts could be developed, evolved and adapted to the increasing system time constraints, variability, uncertainty and complexities [Article 1, 2, 3] (see Figure 9).

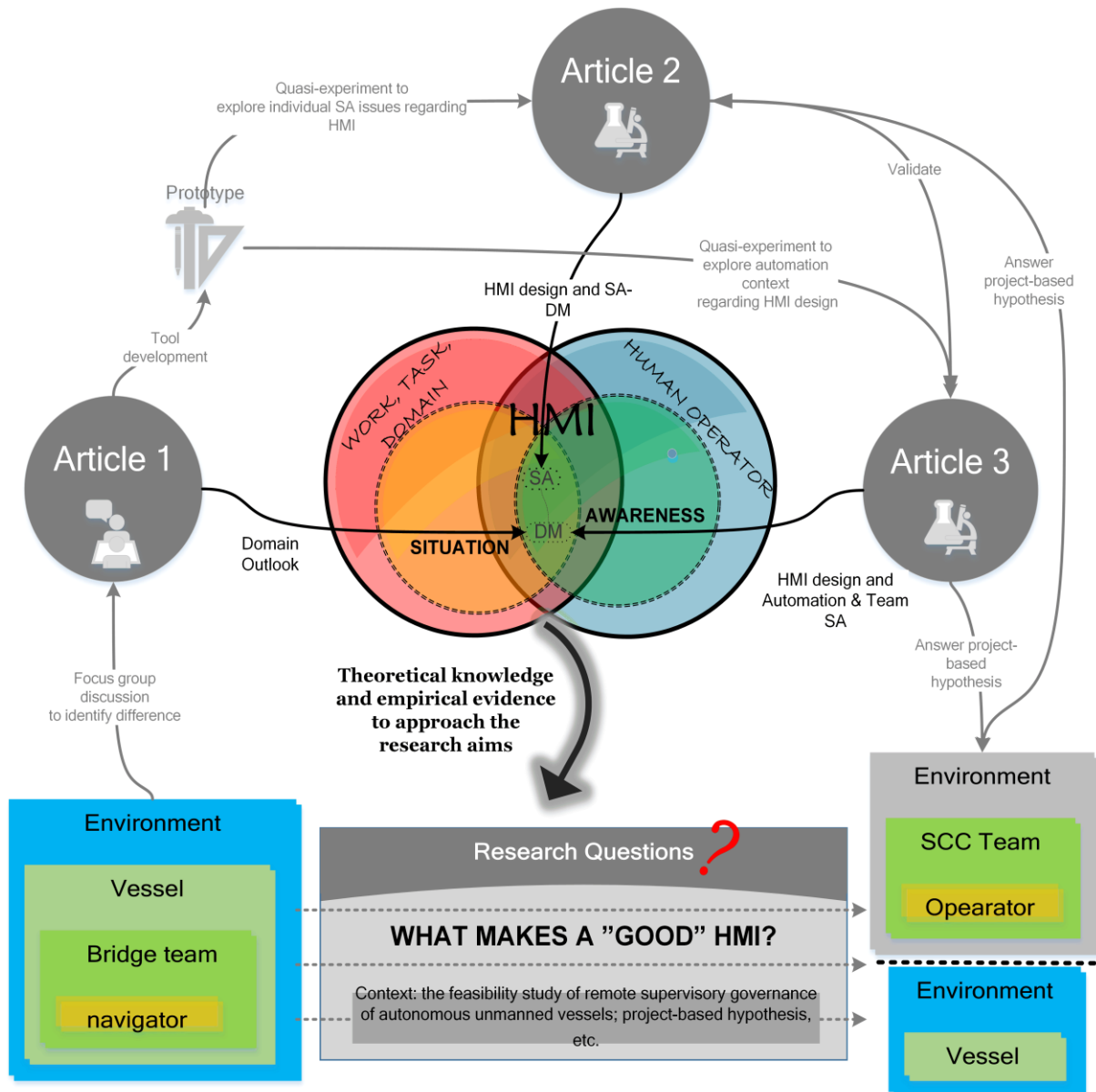


Figure 9. Research synthesis, paradigm and overall methodological approach

The process of our scientific investigations considered both inductive and deductive reasoning approaches. For instance, the major project hypothesis assumed that the SCC could be designed as a migrated bridge system ashore to maintain operators' SA, but it was provisionally rejected according to the results identified in Article 2 and 3. This suggests the importance of the analysis on the contextual constraints in a new task in the outline of the theoretical framework regarding HMI design and implies the context-sensitive properties of the research. The knowledge was accumulated in a non-linear way and interpretive qualitative methods in the research paradigm were primarily selected. Paradigm is a term coined by Kuhn (1962), "an integrated cluster of

substantive concepts, variables and problems attached with corresponding methodological approaches and tools”. A large proportion of complexity of the investigation is grounded on the mixed structure of scientific framework and project-based concepts and assumptions. It is critical to use suitable methods to acquire the scientific truth that is not only based on the objective criteria¹ but also subjective worldview. For example, the system prototype mentioned earlier in the MUNIN project had not developed when the article 1 was published; there was even no such a SCC in the world up till today for operators to remote monitor and control autonomous unmanned vessels; the onboard navigational operation is already one complex joint activity today (National Research Council, 1994) but it is supposed to move onshore. The need to explore more different dimensions of unknown social phenomenon at the starting point of the research is apparently over the need to establish causal links through empirical evidence.

3.2 Methodological Tools

The methodological tools chosen cover data collection and analysis. The selection and utilization of the tools is generally in accordance with structure mentioned earlier to explore the experiences of the human agents in using the *ad hoc* HMI for supervisory tasks.

3.2.1 Focus Group

Focus group was utilized as a data collection method to systematize the centralized situation onboard and explore the underlying shifted human factors in a distributed system. A integrated Lightweight Qualitative Data Analysis approach (Goodman, Kuniavsky, & Moed, 2012) was utilized to analyse the focus group discussion. At the starting point, focus group is suitable for identifying problems, seeking to solve problems from the stakeholders’ view with an exploratory research manner (Ivey, 2011). It also can provide insights into the sources of complex behaviours and motivations (Morgan & Krueger, 1993). It serves well the purpose of exploring the affected aspects of human factors regarding maintaining SA and the operator’s behaviours onshore. Although focus group cannot substitute usability test and observation of product in use to evaluate the HMI of certain product, it can underpin the research of the human factors in complex systems (i.e. perceptual factors, SA and decision support).

3.2.2 Grounded Theory Analysis

Grounded Theory analysis was used to establish codes and categories in order to form theoretical framework (Corbin & Strauss, 2008). MAXQDA 10, a computer analysis assistance tool was used for qualitative text analysis process (Kuckartz, 2014), including the transcription of the debriefing answers, interpretation of texts, memo writing, open coding from the raw data in terms of properties and dimensions, axial coding for relating concept to each other. The existing frameworks in ship-sense (Prison, 2013), the memos and diagrams obtained from the portrayal of relationships between emerging concepts were constantly compared to each other

¹ Post-positivists reject the idea that any individual can see the world perfectly as it really is. We are all biased and all of our observations are affected. (<http://www.socialresearchmethods.net/kb/positvsm.php>, access date: 2015-10-20)

with the comparative analysis method (Patton, 2002). Real-world phenomena observed in the scenarios and recorded in the interviews finally drive the analysis to explanatory propositions regarding SA and HMI.

3.2.3 SART

The Situation Awareness Rating Technique (SART) is a post-trial subjective rating technique that was originally developed for the quantification and validation of pilot SA assessment (Taylor, 1990). 10 dimensions of the human-system integration were inquired for the measurement of operator's SA in order to evaluate the prototype of shore-based decision support system: familiarity of the situation awareness, focusing of attention, information quantity, instability of the situation, concentration of attention, complexity of the situation, variability of the situation, arousal, information quality and space capacity (Taylor, 1990). It requires participants to subjectively rating each dimension on a ten point rating scale (1 = Low, 10 = High) based on their performance of the task under analysis. Although the method was criticized for the correlation between performance and reported SA and participants do not necessarily know they have low SA (Endsley, 1995a; Stanton, Salmon, et al., 2006), it is non-intrusive to primary task performance and has high in ecological validity (Stanton, Salmon, et al., 2006). Besides, the debriefing provided invaluable information to support the data gained from SART and Quality In Use Scoring Scale (QIUSS) data.

3.2.4 QIUSS

While SART was probing the subjective ratings on different dimensions of the situations, QIUSS (Jones, 2008) was utilized in conjunction with SART to evaluate the HMI's Quality In Use (QIU). QIU is referred as the capability of a product system to enable specified users to achieve specified goals with effectiveness, productivity, safety and satisfaction in specified contexts of use (ISO/IEC, 2004) and QIUSS was developed to give a very simple broad measure of QIU - a lower score is assigned as a poor attribute to the dimension and a high score reflects a positive rating (Jones, 2008). The rater was asked after each scenario trial about the participants' subjective evaluation of the MUNIN prototype's HMI on effectiveness, productivity, safety and satisfaction.

3.3 Procedures

This section delineates the actual procedures considered for each appended article within this licentiate. Each article contributes direction, as a standalone paper, to the discussion chapter.

3.3.1 Article I: Comparison of situation onboard and onshore to reach the prioritization of design

This article explored the master mariner students' perspective of different situations of ship-handling in a bridge and in a shore-based control centre as well as the changing aspects of human factors that we need to prioritize in design to meet the needs of operators. The shore-

based control centre is based on the MUNIN project's context. The shifted human factors for supervisory tasks are discussed.

Ten undergraduate students in Chalmers University of Technology voluntarily took part in the focus group interview. The participants' background was similar: they were studying the same master mariner program and they all had sea experience prior to the focus group interview, however not as officers. Their previous active time at sea varied between 9 to 33 months, with a mean of 16.5 months ($SD = 7.2$ months). Only one participant was Mexican-Swedish while the rest nine participants were all Swedish. Their ages ranging from 22 to 41 years old, with a mean of 27 years old ($SD = 6.9$ years). One of the participants was female (10%) while the rest were males (90%). Out of the ten participants, only one person (10%) didn't have ship manoeuvring and navigation experience, the rest (90%) all had experience in ship handling in the bridge, either alone or under the supervision of the captain. Fifty percent of the participants had the experience of remote ship monitoring or controlling, including in the simulation environment. Besides, fifty percent of the participants had been previously involved in ship or workplace design work (ships, systems, tools). Forty percent of the participants mentioned that they also had working experience in maritime-related activities at the same time as they studied, mainly being able seaman and working for passenger vessel.

The focus group interview process was recorded by a voice recorder for analysis after the interview. It lasted for approximately two hours. Meanwhile, the focus group interview assistant was taking the field notes on the participants' discussion. All participants were briefed about the MUNIN project with the concept of a dry bulk carrier sailing without helmsman for deep sea under constant remote surveillance.

The first questions asked the participants to discuss the possible actions to execute ship-handling that would actually correlate with their past ship manoeuvring experience: *What actions will it take to monitor and manoeuvre the ship onboard today?*

The replies from the participants were continually listed on the whiteboard. Then the second question asked the participants to envision an operators' possible action in a SCC: *What actions will it take to monitor and manoeuvre an autonomous unmanned ship from a SCC?*

With the actions and tasks being discussed in both onboard and onshore situations, the third question asked the participants to identify the changing aspects of human factors under these two circumstances: *From the perspective of human factors, what is the difference when we shift ship handling from being onboard to being onshore?*

Lastly, the participants were asked to prioritize the key aspects of the human factors that would require special attention, especially from an operator-centric perspective in the SCC.

After the focus group interview, the ordering scheme for the data with prioritized feature lists was initially created and summarized. Then the Lightweight Qualitative Data Analysis

approach (Goodman, Kuniavsky, & Moed, 2012) was taken through by analysing the audio recordings together with the field notes as well as the lists.

3.3.2 Article II: Identification of human factor issues in the operator's supervisory tasks in the field

Previous studies suggest maintaining adequate SA as a primary challenge regarding the design of human-centre automation. This article explored the human factor issues in use of the MUNIN project's shore-based prototype for operator's supervisory tasks. The scenario-based trials were administered to evaluate the HMI of SCC prototype and the situation awareness of the operator. The qualitative data collected from the post-trial interviews identified critical gaps in the HMI regarding distributed decision support.

Five participants (4 males with backgrounds as master mariners and 1 female engineer) were invited to take part in the scenario-based trials and debriefing interviews. Their ages ranged from 28 to 49 years with a mean age 39 (SD = 8.9) years. Previous experience at sea varied between 3 to 18.3 years, with a mean period of 10 (SD = 6.8) years. For the four master mariners, their time as a deck officer ranged from 2.4 to 8.6 years, with a mean of 5 (SD = 2.5) years. All four master mariners had experience in navigating ships in a simulated environment. All participants signed a written consent form about the anonymous and ethical usage of their data. They were assigned different IDs (1-5) to act as the operator, captain and engineer in scenarios.

Five scenarios, developed by subject matter experts, were presented to the participants over a two-day period. The scenarios were about identification of engine malfunction, collision avoidance, weather routing, and handover procedure to manned vessel. Prior to the data collection, all participants were given approximately 2 hours of familiarization information, including half an hour briefing on duties and responsibilities of personnel in SCC. This was followed by an introductory presentation about the overall concept of unmanned ship and the HMI. Each participant had approximately one hour of further instruction and individual practice on the technical system. After that each was assigned "roles" within each scenario, as operator, captain or engineer. All scenarios and post-scenario interviews were recorded by a video recorder for further analyses. Direct observation approach by an onlooker observer was used and field notes were documented (Patton, 2002). All participants in the scenario were encouraged to "think-out-loud" (Lewis & Mack, 1982). After each scenario, the participants were asked standardized open-ended interview questions to examine their sense making, decision making, situation acquisition as well as opinions over the team performance. From the operator-centric perspective, the critical issues in the HIM regarding distributed situated decision support were addressed.

The pre-analysis was built on the literature review of ship handling (Prison, 2013; Prison et al., 2013), SA and SA-oriented design (Endsley, 1988, 1995b, 2011, 2015b). It identified several underpinnings as a starting point for the comparative analysis using Grounded Theory (Corbin & Strauss, 2008). MAXQDA 10, a computer analysis assistance tool was used for coding,

comparison, memoing to keep track of the ideas and emerging patterns in qualitative text analysis (Corbin & Strauss, 2008; Kuckartz, 2014).

3.3.3 Article III: Identification of human factor issues in the operator's supervisory tasks in the field

Seven participants (4 males and 1 female with backgrounds as master mariners and 2 females as engineer) were invited to take part in the scenario-based trials and debriefing interviews. Their ages ranged from 27 to 48 years with a mean age 38.9 (SD = 8.7) years. Previous experience at sea varied between 0.25 years to 12 years, with a mean period of 7.5 (SD = 6.4) years. For the five master mariners, their time as a deck officer ranged from 0.6 years to 10 years, with a mean of 4.7 (SD = 4.7) years. All five master mariners had experience in navigating ships in a simulated environment. All participants signed a written consent form about the anonymous and ethical usage of their data. They were assigned different IDs (1-7) to act as the operator, captain and engineer in scenarios.

Seven volunteer participants, all being either vessel traffic service operators, master mariners or ship engineers underwent six scenarios. Each was assigned "roles" within each scenario, as operator, supervisor, captain or engineer. Following each scenario, each participant was asked to complete a Situation Awareness Rating Technique (SART) questionnaire (Taylor, 1990) and the Quality In Use Scoring Scale (QIUSS) scale (Jones, 2008). A debriefing questionnaire was administered and included questions relating to HMI design and usability.

Both qualitative and quantitative data was collected to get a better understanding of how each participant felt they obtained and maintained situation awareness (SA) and how effective the HMI was in achieving these states. The data from the debriefing was transcribed and analysed with comparative analysis method (Patton, 2002). It was also served to interpret the SART and QIUSS responses.

4 Results

This chapter highlights the findings from the included articles to provide a discussion basis. The highlighted results not only aim to discover various system aspects but also are expected to walk the readers through the applied context of the MUNIN project and assist the systemization of pieces of puzzles pertinent to HMI for future framework development.

4.1 Article 1

The purpose was to explore the different situations onboard and ashore though the focus group discussion and further explore underlying shifting human factors that are extremely important for designing the HMI to support the SCC operators. For the situations onboard, checking navigational instruments and the surrounding environment was identified as the participants' primary activity on a bridge while the kinetic "feeling" (e.g. "standing wave", "rolling" or "sense of balance") of the vessel was also indispensable. In an envisioned SCC, the participants believed different actions would be taken to monitor and control vessels under such a different work environment, thus addressing different requirements on the HMI of the system and even the whole SCC sociotechnical system was necessary - the primary functional requirement was to provide the full coverage of ship-centric information, from electronic charts to observable sensors readings while the non-functional requirements should cover usability (e.g. ease of use especially avoid information overwhelming), availability (e.g. real-time communication), reliability (e.g. back-up system), maintainability (e.g. handling urgent maintenance request), plus the competence requirement of the operator. Overall the shifting presentations of human factors were basically clustered into seven categories, with an overview outlined in the Table 1. SA is recognized as the most important factor to focus on.

Table 1. The overview of the changing aspects of human factors from ship to shore for ship-handling

Human Factors	Presentation of these factors	Participants' highlighted views
Sense	Visual, auditory, sense of smell, kinetic feeling, sense of balance	<i>"ship starts vibrating and pitching when changing the course a bit, but these senses are lost ashore"</i> <i>"Everything got closer ashore"</i>
Perception - Cognition	Mental model, decision making, situation awareness , information overloading, stress, trust in the system	<i>"You may pay attention to parameters that don't matter or are wrong and you worry for nothing."</i> <i>"Receiving much more information but you can't discern what matters to you as you did onboard"</i> <i>"When you're onboard, fear is simulating but you're less stressed ashore. Complacency. Maybe too relaxed."</i>
Workspace	Working environment, ergonomics, hardware, software	<i>"Only rely on instruments ashore"</i>
Maintenance	Back-up systems, maintaining approaches	<i>"A big part of the ship work is maintenance"</i> <i>"What happen if there is a malfunction or emergency"</i>
Risk	Risk assessment, shifting risk	<i>"Risks for other boats around"</i> <i>"Not that risky being onshore"</i>
Organization	Expertise, structure, roles, education/training	<i>"Computer engineers for the operator ashore would be good since they monitor ships through computer. Seafarer would not need that"</i>
Legal perspectives	Regulations, laws	<i>"Who is responsible if the ship is in international waters"</i>

4.2 Article 2

The results first discovered the relation between SA and Harmony. Harmony is about a balanced way of controlling the vessel according to contextual constraints (Prison, 2013; Prison et al., 2013). The “gut feeling” mentioned in article 1, is actually the “ship sense” (Prison et al., 2009), the skill to achieve the “harmony goal” – by manoeuvring the vessel, the ship-handler is constantly balancing his own capabilities and the task demands. The ship-handler constantly uses his mental model as a higher-level SA enabler to interpret the surrounding perceptual information and understand how things are working and evolving in the situation, as the Harmony-SA model outlined in Figure 10. When the ship-handler becomes the operator in the SCC, the changes in structural relationship between SA and constituents of harmony reveal four discrepancies in SA requirements (Endsley, 2011): technology analysis (D1), environmental conditions (D2), operational requirements (D3, D4), and user’s characteristics (D4). The changes in SA requirements differentiated the design of this SCC system from the conventional design for the ship bridge.

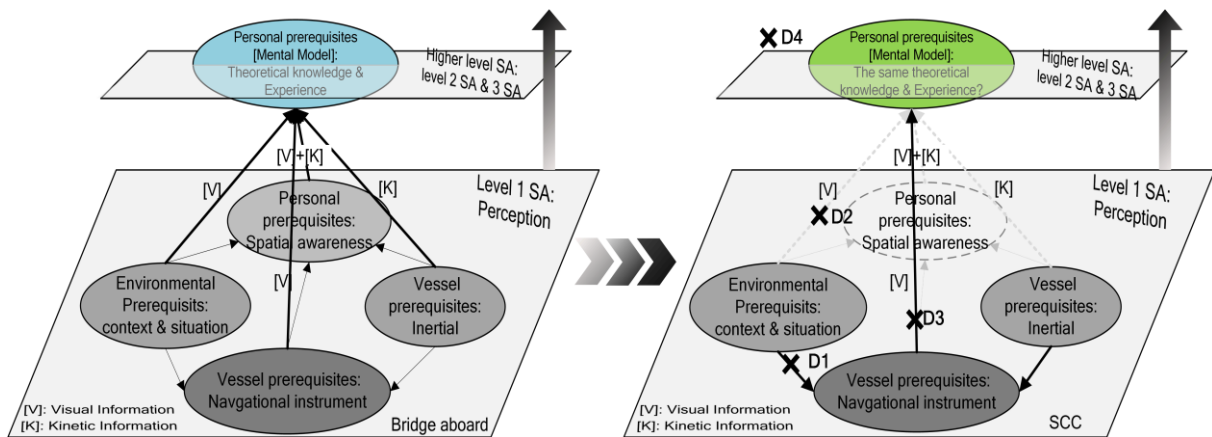


Figure 10. Four discrepancies in SA requirements were identified in the evolving harmony-SA model.

The Grounded Theory analysis combined with the SA requirement changes indicated the gaps in the current shore-based system that undermines the operator’s SA and team SA.

Gap 1: Risks of detection failure of abnormality around the vessel or generation failure of alarms as the prerequisites for development of level 1 SA

Gap 2: Loss of ship sense, a vital perceptual approach to develop level 1, 2 SA - risks of detection failure of abnormality around the vessel

Gap 3: Degradation of the vigilance, discoverability and comprehensibility to develop level 1, 2 SA due to the heterogeneity of the received information, passive monitoring pattern, and insufficient display information

Gap 4: Incompleteness of mental model to influence compression and projection of the situation in level 2, 3 SA

Gap 5: Vagueness of the regulations and operational protocols as well as ill-structured organisational hierarchy

The gaps could reflect the primary perceptual and operative challenges posed on the operators and his team in the SCC, which was intrinsically influenced by being geographically distributed and could also be externally mediated or deteriorated by the HMI for remote supervisory control. Besides, the HMI layout of multiple displays for multiple vessels sometimes confused the operators about focus of the attention, despite they adapted to the flag-based alarm mechanism rather efficiently. In general, the prototype SCC alarm system made the participants feel difficult to understand how critical the situation was at sea and how it would evolve in the future. The result revealed that these gaps were tightly correlated to the conventional thought of designing SCC as it was migrating the bridge to the SCC, thus the hypothesis that the SCC could be designed in the same approach as it was designed on a bridge was declined. These correlated gaps from the simulation trials reflected how HMI that did not fully accommodate the requirements in a distributed HAS were contributing to the degradation of individual and team SA and decision making capabilities; this suggested that appropriate levels of SA could not be maintained without the support from a reliable HMI which should well-manneredly integrate “situation in the wild” and “awareness in the mind”.

4.3 Article 3

The study presents aggregated results from SART across the six scenarios for all participants and each dimension of SART (Taylor, 1990) in Figure 11 and QIUSS in Figure 12. It demonstrates that the concept of unmanned autonomous vessels needs to evolve. While the participants were highly skilled mariners, none have experienced a sociotechnical system as defined in this SCC context, which provides rather important indications on how the context could influence the design.

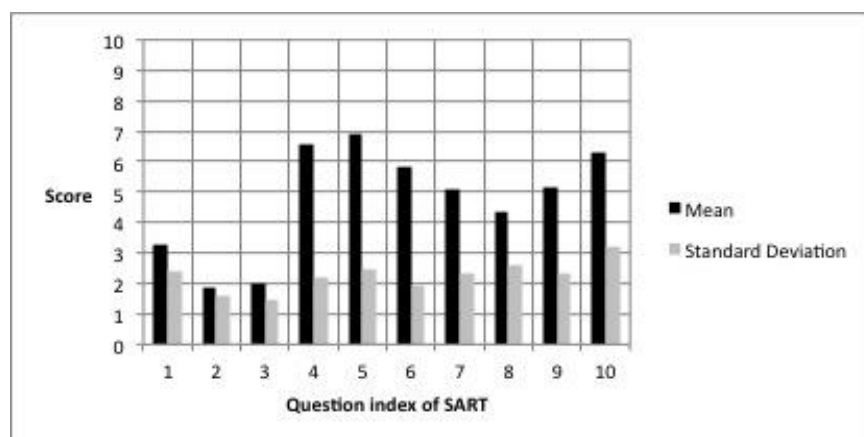


Figure 11. Aggregate results across the six scenarios for all participants and each dimension of SART

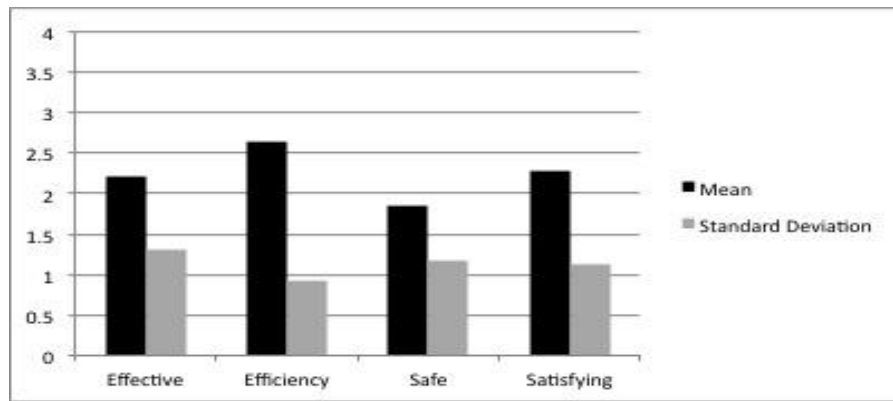


Figure 12. Aggregate results across the six scenarios for all participants and each dimension of QIUSS

5 Discussion

The whole reason for doing science is about discovery and posit a credible explanation for this event (Harris, 2012). Loss of presence in within distributed sociotechnical system can lead to a critical perceptual bottleneck and inability to verify information. This could negatively impact upon an operator's behaviours and performance. It will likely have an impact on the development of SA, mental models, and further decision-making capacities. The way to mechanically replicate a centralised sociotechnical system (e.g. bridge onboard) in a distributed situation (e.g. ship-shore context) has great potential risk to bring about automation bias and degraded Team SA. From the perspective of team performance, the HMI, as the main Shared SA platform, is used to explore the real-world "situations", could also greatly influence the development of shared mental model. While traditional technology-centred perspectives believe it is usually usability issue causing issues with the HMI or because of insufficient training, this discussion on perceptual, cognitive, environmental and organizational factors in this study argues that the design of HMI is not a simple matter of constructing graphical user interface. The contextual factors in the system must be both accounted and accommodated by the HMI. A decision support system shall not intend to inform the team about the decision to make, but support and inspire them by affording diagnostic resources and disturbance-absorbing reversibility. The system shall not only support data transfer and visualization, but also the process and context in which data are received, utilized and understood for consensus decision-making.

This chapter is not only concerned about interpreting the results from the papers from the previous chapter, but also to examine these in an aggregated manner within the context of the wider scientific literature and holistic human-machine systems. It aims to provide a sound theoretical foundation from which we can develop HMI design principles to apply within the domain. The framework of Ecological Interface Design shows us another possibility to improve the transparency of the complex Human-Automation System by an efficient development of mental models via properly designed HMIs. A key systemic thought is that the HMI needs to weave the elements of *situation* and *awareness* together, resulting in a formulation of new forms of *situation awareness*.

The HMI concept discussed in this licentiate has been intrinsically evolved and developed towards designing for use and resilience in a complex sociotechnical system. It is important to realize that not all errors can be totally removed through "perfectly" designed HMI or training but the errors could be mitigated in a resilient system framework. The training programmes and organizational hierarchy has to accommodate the distributed characteristics of the sociotechnical system and allows teamwork in a coordinated and resilient manner. This provides future research opportunities with regard to a more comprehensive cognitive work analyses as a general theoretical foundation to foster the HMI concept as a system concept.

5.1 Situation Awareness

Endsley (1995b) defines SA as “knowing what’s going on” and, more formally, as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (p. 36). SA has become a widely used and empirically supported cognitive engineering concept within the human factors domain (Parasuraman et al., 2008). In the focus group study, SA was listed as “the most significant key to focus” for the design of the SCC system among all the important aspects to consider by the participants; In the other two quasi-experiments, the results of SA barriers, subjective quantitative measurement and qualitative debriefings has revealed the prominence of SA in the design of HMS, suggesting the functioning role of HMI and other system factors in the process of SA development, decision making and performance of actions in order to support individuals and teams in both regular and unanticipated situations.

5.1.1 Perception and Presence

The first level of SA is to perceive the status and dynamics of the elements in the environment through visual, auditory, tactile, taste, olfactory sense or combined (Endsley, 1995b). The focus group discussion indicated that visual perception has significant weight in all the sensations in the ship-handling activity while the supplementary “feeling” is as well of paramount importance for the ship-handler to perceive heterogeneous feedback simultaneously from another information source, e.g. feeling the vibration of the vessel. This tacit and gut feeling is interpreted as the “ship sense” (Prison et al., 2009), which can more efficiently inform the ship-handler the ship status than the electronic displays and subtle dynamics within the environment. For instance, the kinetic movement and vibrations on a bridge could imply the both the internal ship status (e.g. full loaded cargo) and external environment effects on the manoeuvrability of the vessel (e.g. climate or terrain). Although the “ship sense” is very critical for the development of level 1 SA on a bridge, it is on the other hand quite limited to provide a precise measurement of the system status but rather being a “trend indicator” of the overall situation. Therefore the HMIs of the classic “Integrated Bridge System” (IMO, 2002), typically the electronic displays like radar and “Electronic Chart Display and Information System (ECDIS)”, need to provide the ship-handler more precise information about the desired state of the system and the situation overview. Consequently the design on a bridge ought to be highly manoeuvring-oriented and accommodate the process of information acquisition through different perceptual channels to complete the level 1 SA.

The results from article 2 and 3 highlighted the importance of level 1 SA in relation to the design as the perceptual challenges in the SCC literally could bottleneck the development of the operators’ SA. They can neither directly perceive the information from the environment nor feel the kinetic movement from the vessel. By reading digital parameters from the monitoring programmes, the operators receive very different perceptual cues compared to onboard situation where they may see, hear, smell, and feel. In another words, the operators could not feel the same way in the SCC as they used to feel on a bridge, which is important in the development of situational presence (Barfield & Hendrix, 1995; Witmer & Singer, 1998). The direct effect

of the lack of presence in the SCC would be the huge perceptual limitation in a distributed sociotechnical system. Computers become prioritized tools as they serve as the exclusive perceptual information providers to facilitate an operator's achievement of level 1 SA. This mainly explain that when everything was normal in the scenario-based trials, the operators became less vigilant and more passive in monitoring activities with certain degrees of complacency, as they were not actively engaged in ship's operations "at the distal end". However when there was an abnormality, the operators felt unsafe or became confused even though the HMI was displaying pertinent information. The contrasting behaviours has led to two significant conclusions why a sense of presence is important in an HMI design:

1. One reason why presence (i.e. "ship sense" in the case of ship-handing) is vital is because it enables the subjects to verify information through multiple information sources, each of which is associated with different levels of reliability. Ship-sense or presence allows a ship-handler to physically validate the virtual data being presented to them through the electronic displays. In the SCC the operator became quite confused and scored "safety" as the lowest measurement in QIUSS questionnaire due to the lack of the means to verify the data but only could "blindly" trust the dashboard system. In contrast with the bridge design, at least parts of the SCC design emphasis need to put on the presence development to achieve "perceptual illusion of non-mediation" (Lombard & Ditton, 1997). Proper feedback through visual, auditory or even kinetic data is critical in the HMI development for distributed sociotechnical systems.

2. Another effect of presence that cannot be overlooked is how it was assisting the human operator to constantly build the SA in a dynamic non-linear process with varying complexity and demands of the situation. It should be mediated by the HMI in a complex sociotechnical system. Admittedly the amount of SA that can be achieved is limited by the finite attention resource of an individual (Endsley, 2011), but presence enables him to actively pay attention to the prominent dynamics and evolvement of the situation. The debriefing data in the trials ascertained that the operator's SA was sharply developed because the attention-getter was merely the alarm from the HMI and there was even no audible alarm in the first prototype. From the interaction's perspective, sound/haptic feedback could probably feature well in a SCC design. The results suggest that there was huge risk of missing the alarm or late notice if the HMI did not take into account how the constraints in context could greatly influence the performance of perception and attention. The abruptness of the arrival of the abnormality also implies that the HMI used in supervisory control tasks ought to consider to integrate the operator in-the-loop as early as it can. For instance the presentation of the "trend / evolvement of the situations" could be more important than "parameters in the situation" in the early development phase of SA, given that the SCC and its organisation is very much like the one onboard and the functions stays similar although the context is hugely different.

5.1.2 Mental Model and High Level of Understanding

In the classic information processing cycle proposed by Neisser (1976), human mind creates a cognitive scheme of the world and directs his action to look for the anticipated aspects of the information. The sampled results from the world would in return modify and update the internal

cognitive map. The mental model in Endsley (1995b)'s SA and decision making model could be considered as a key construct to develop SA which is built on the an interactive cycle of information processing. A mental model is a systematic dynamic understanding of how the world works, including both semantic knowledge and system knowledge (Endsley, 2000). For example, when an operator is interacting with HMI in the SCC, the operator is constantly building and updating the mental representational map about how the system is operating and functioning from the feedback of the system.

The relationship between harmony and SA and their connections to the identified gaps from the trials have indicated that the mental model is essentially the key enabler for achieving higher level of SA by two primary means: 1) informing the operators what the information means and 2) how critical the situation is. When an operator is building a “mental image” (i.e. a mental model) about the dynamic situations, feedback from the HMI becomes important as it will influence the adaptability of the mental model. People normally don't read user manual before using iPhone for the first time not because they learnt the system enough but the well-design HMIs with proper feedback provide great possibilities to efficiently and effectively develop the user's mental model to quickly “adapt to the world”. The QIUSS result reveals that the participants were generally neutral about the automated system and dashboard interface employed in the SCC. This might suggest that these new technologies indeed posed some challenges to the operators while the HMI was probably mediocre at facilitating the development of their mental model, given that all participants had no real previous experience with the prototype prior to the simulation test. Perhaps this exposition could be accounted with a dialectical view:

For example, the SCC prototype is designed as a colour-based flag alarm system which can provide corrective actions for detected abnormalities, integrated with other conventional navigational instruments (e.g. ECDIS chart). The intention to have the green-yellow-red flag structure plus conventional procedures to indicate the status of the automated process has at least two advantages: In terms of perception and attention, the design optimizes the usage of the attentional resources by providing the aggregated flag for each cluster of information on the dashboard. It allows the operator scanning the overall status of all vessels under surveillance efficiently, which gives some explanation to the positive feedback on how operator intention was focused in the tasks from the SART data and the highest score on system efficiency from the QIUSS data. More importantly, the incorporation of the flag-based mechanism (e.g. red means urgent issues that need to intervention) and conventional navigational techniques is in fact using the metaphors that the operator has been familiar with in the real world. With the “default information provided by the mental model” (Endsley, 2015b), this user interface provides the instinctive “affordance” (Norman, 2013) for the operator to manipulate to search for the desired information and allows a consistent development of the internal cognitive schema or mapping pattern. As the operators preceded through the exercises, it seems like they were more familiar with the instructions and pattern recognition. This corresponds to the advantage of mental model, *categorization mapping* that “people has the ability to generalize from existing experience to new ones” (Endsley, 2011, p. 23). Some of them even reported that

they intuitively knew the situation was critical because of the red flag but not necessarily understand the situation (level 2 SA) or more interestingly, they foresaw the situation would probably evolve to a red flag (level 3 SA) without fully comprehension of the situation (level 2 SA). It ascertains the three levels of SA are not necessarily developed in a linear-pattern (Endsley, 2015b). While a human-centered HMI could nourish the mental model to dynamically cope with the changes from the environment, an ill-designed HMI could also induce an errant mental model which can cause confusion, frustration or even human error. As it was mentioned in the results section (4.2.2), frequent switching between vessels could lead the operator to misbelieve that he was monitoring vessel A while vessel B was actually the focus of attention. After all, the task was to monitor multiple vessels through the same set of displays. The design of HMI should allow the operator to map the virtual representation to real world artefact effectively, and standardization of future system applications and their implementations is rather critical.

The utility of a mental model stays beyond perceptual level. According to the Rasmussen (1987) model of three levels of performance, the operators' performance in the simulation trials were gradually shifting towards the "rule-based" behaviour (e.g. detect red flag as the "signs" – realize it is critical and needs intervention – click the red flag) towards the skill-based behaviour (e.g. detect the red flag as the "signals" – click it and watch the sea chart to locate the vessel). However, the real challenging phase came right after this seemingly smooth stage, where the operators generally reported that they had an "unsmooth period" to figure out the underlying causes of the situation and determine what to do next. The SART data from the trials and gap analysis also suggested their SA was challenged in the process of achieving high level of understanding. This was typically observed in the engine malfunction scenarios when the operators might receive never-before-seen engine alarms messages or in collision avoidance scenarios when the conflicting target unusually violated the COLREGs (i.e. International Regulations for Preventing Collisions at Sea as the "rules of the road" at sea). Although beforehand the operators were advised to seek help from the ship-engineer or captain if necessary, the protocol for handover command was not designated to be mandatory. With the unfamiliar task conditions and vagueness of the regulations, the operators' performance was quickly shifted to the "knowledge-based" behaviour at a higher conceptual level, where their moves were more "goal-controlled" but paradoxically "blindly" (Rasmussen, 1987). Such phrases were frequently heard from the participants' think-aloud process, "what is the meaning of this...I want to find but where...I am not sure if this means...". The critical purpose of HMI at such moments is to deliver meaningful symbols to the users and assist them to form the representation of the difference between the actual state and desired state in the time-space environment. It is not a process of making decision for the user but helping them to understand the unanticipated events and support their planning for the contingencies. The HMI design needs to make sense in order to support sense making. From the lens of "data/frame theory" which was framed to delve the nature of sense making (Klein et al., 2007), we could argue that, the capability to support a user to make sense of the world of a HMI is largely due to how efficiently and effectively it was assisting to build the "frame" to select the "data" and use the existing "data" to construct appropriate "frame" in a reciprocal manner. This understanding on

HMI's requirement of decision making support actually shares much of the views interpreted from Endsley (1995b)'s SA model – under such unfamiliar and complex circumstances, HMI should activate the schema and appropriate mental model to prompt the user to actively utilize his fundamental knowledge and direct the intentions in the goal-oriented pattern. For instance, when some other vessel in vicinity violates the COLREGs or some problems occurred in the engine, salient cues regarding the manoeuvrability of the vessel would be very critical for their sense making and decision making. In fact, such information would directly provide assistance to level 3 SA while the developing mental model had not matured to a point where the future status of the system could be derived.

It is important to realize that the analysis on mental model is critical to study HMI design for complex Human Machine System, as efficiency of human in coping with complexity depends upon “the availability of a large of repertoire of different mental representations of the environment from which rules to control behaviour can be generated *ad hoc*” (Rasmussen, 1987, p. 258). Good interface design does not necessarily result in good SA because it might only put efforts each of the component rather than the relations between the system components and interactions between human and user interfaces. To truly support the operator's high level of understanding and their sense making process, the design of HMI needs to address both the perceptual or physical and the cognitive attributes of the operator. This would allow him to update the mental model more efficiently to interpret the feedback and understand the status of the system quickly as well as to be able to incorporate the goals in the mental model.

5.1.3 Team Performance

An operator needs to comprehend the status of automation via HMI, but this, alone, is not sufficient. How the team members that the operator would likely to interact with in any stage of the task process assesses the situation and plans the solution is a crucially important system factor. It might significantly contribute to an individual's decision making and problem solving performance. While the majority of the research to date has focused on individual SA, the context of this research requires an understanding of the Team SA, how it is obtained, maintained, transferred and sustained, as long as their connection to the organizational factors.

5.1.3.1 Team SA and Shared SA

Endsley (1995) defines “Team SA” as, “the degree to which every team member possesses the SA needed for his or her job” (p. 39). This means that each team member needs to have the SA required for a specific duty in order to achieve an overall team goal or operational success. On a bridge, every crew member might have his own SA requirements for his specific role but the overall goal is to achieve the safety of vessel, cargo and people. Meanwhile as a team, they work interdependently to achieve their sub-goals. In a SCC, the operator may need the help from a captain and ship engineer to analyse issues within a scenario. This means they have some overlap in SA requirements and sub-goals as the basis for their Shared SA (Endsley & Jones, 2001). Shared SA refers to “the degree to which team members have the same SA on shared SA requirements”, therefore “the team member have the same understanding of what is

happening on those SA elements that are common” (p. 48). Shared SA may be constructed through information flowing between team members and may not necessarily be unidirectional. Due to the interdependence feature of a team (Salas, Dickinson, Converse, & Tannenbaum, 1992), poor Shared SA deteriorates the Team SA while good Shared SA doesn’t necessarily lead to good Team SA. Endsley and Jones (2001) models the Team SA from the following perspectives: 1) Sharing of SA requirements; 2) Devices that could help teams form shared SA including verbal and nonverbal communications, shared displays and shared information; 3) Team SA mechanism, the development process of a shared mental model; 4) Team SA processes that the team employ (through formal training and operational protocols). We would like to discuss how the HMI as the supporting technologies can have a huge impact on the SA flows between each individual, the development of a shared mental model, and communication to satisfy the Shared SA requirements among team members. This is not only to draw inferences about the design principles for such a distributed supervisory system like SCC, but also for probing insights about team settings, optimization of teamwork process and organizational hierarchy, and contextual factors in the sociotechnical system.

While the SCC concept has been described within the overall project requirements, how a team of participants unfamiliar with the concept interacts via “Shared SA Devices” might be challenging. From the physical level, moving people from a centralized ship environment to shore-based remote monitoring office environment would severely reduce the availability of various sources of SA elements that are inherently obtained from being onboard. One hidden advantage of bridge officers sharing the same working environment (i.e. including motion, olfactory, visual, auditory, and tactile elements) is that it synchronizes their perceptual senses and facilitates the development of the partially shared mental model in a coordinated fashion even without requiring extra communication. Each one of them receives the same cues as anyone else onboard, such as feeling the rolling, pitching and heaving of the ship and seeing dynamics from the surrounding environments. Under such circumstances, the shared cognitive resources (i.e. the shared mental models) enable people to have a great possibility to achieve a higher level of common understanding in real time by interpreting these cues efficiently. Mosier and Chidester (1991) claim that the use of shared mental models could help the aircrews to achieve better performance with even less communication. However shared mental models doesn’t mean they are identical mental models because team members may not need to share everything they know and in fact they cannot do this either, but failure to build a shared part in pertinent mental models could cause people to have different comprehension and projection based on the same received cues and this would likely result in critical errors (Endsley, 2015). In one of collision avoidance scenarios, a SCC operator was introducing the anti-COLREGs situation to a SCC captain on a shared electronic display. Interestingly enough they first came up with totally different manoeuvring strategies and each one was persuading the other in such a relatively “democratic environment” of the lab until sufficient verbal communication made them reach the consensus in the end. One important cause was revealed from the debriefing questionnaire that the design of the HMI prototype didn’t show the pertinent SA elements on the display so it became a barrier to the development of the shared mental model and SA flows. With the information asymmetry and insufficient communications in the first place and without

the trade-off compensation by the HMI, everyone did not share the same understanding of the situation that further increased the discrepancies in looking for a solution to the situation. It almost led to a “SA black hole” (Endsley & Jones, 2001), “in which one team member would have a strong belief in an erroneous picture of the situation such that he or she would lead others astray and absorb the resources so of the group” (p. 56). The participants then got bogged down in the time-consuming explanation and communication in such critical moments, which implies a huge safety threat to the overall system performance. All these suggest HMI’s important role in influencing both the development of the shared mental model and usage of the other “Shared SA Device” (i.e. communication). As the only medium used to explore the real world “situations”, a SA-oriented HMI may contribute to the synchronization of the SA requirements and system performance much more significantly in a distributed system than it was usually used in a centralized system like on a ship bridge or plane cockpit.

5.1.3.2 SA and Organizational Context

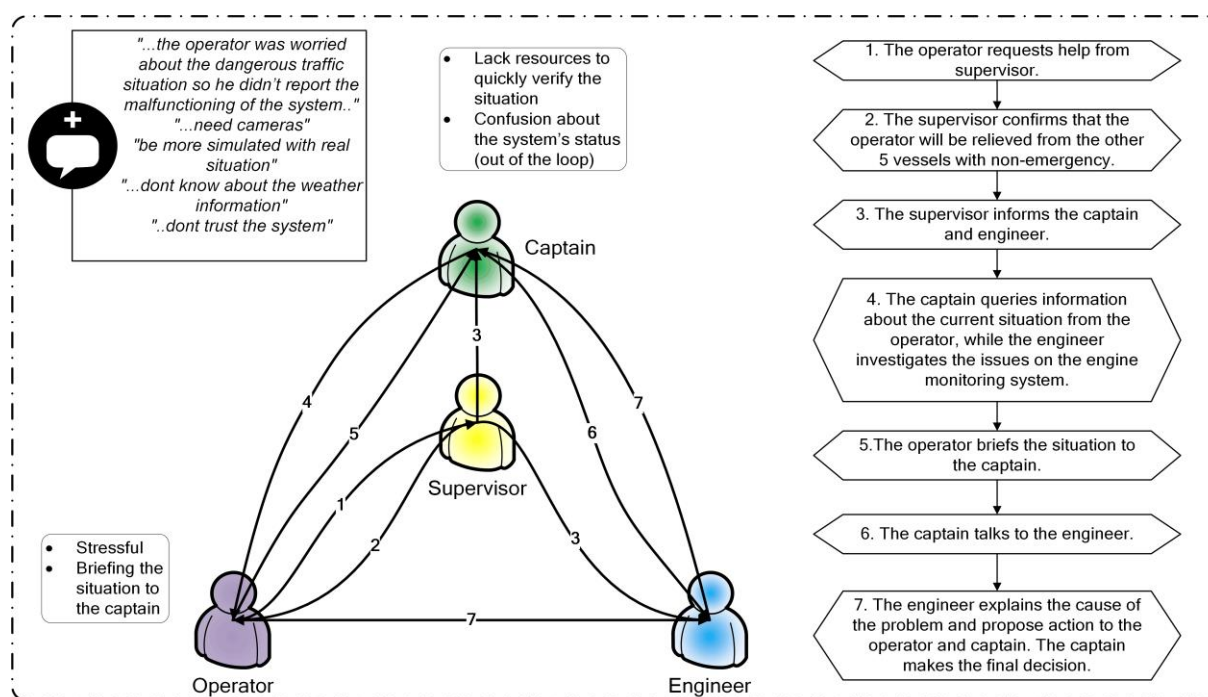


Figure 13. The chronological order when the operator decides to request the supervisor to involve the engineer and the captain for decision making

More issues regarding the relation between the HMI and organizational and social context were revealed from grounded theory analyses and debriefing questionnaires on individual and Team SA barriers. Based on the premise of the MUNIN project, a SCC’s hierarchy was structured in a way that “operator as receptionist, supervisor as coordinator, engineer as technical consultant and captain as final decision maker (the captain was logistically considered to be legally responsible for the fleet)”. From the performance in the tests, the SCC actually relies on a more fluid and sometime flattened hierarchal structure where decisions are arrived through consensus, which is a contrast to a vessel that has clear command and control structures with a primary decision-maker (i.e. the captain). If the operator didn’t feel competent to handle a

situation, as it is the observed case described earlier, then a hand-over via the supervisor to a SCC captain or/and engineer could occur. For example, when the operator decides to request the supervisor to involve the engineer for engine malfunction diagnosis and the captain for final decision making, the event would occur in the following chronological order (see Figure 13).

In the prototype settings, the engineer uses another engine monitoring system to diagnose the situation while the operator briefs the captain about the navigational situation of the MUNIN ship and ships in the vicinity. There are several critical risks and implications to HMI design found in such stressful circumstances:

1. The operator could delay reporting to the supervisor because of over-confidence or he miscommunicated with the captain when there was an engine alarm.
2. The process for the engineer to advise the captain is essentially sharing of SA requirements, which is very important for the team members to have a high level of common understanding of the situation and projection of the future. What the captain and operator would like to get is not the cause of the malfunction “pump injection failure” but its possible impact on the manoeuvrability. For the HMI used by the engineer, it would be optimal to make him know what his own action would influence other people decision making process.
3. The engineer was out-of-the-loop and the shared SA development depends partially on the communication with the captain. But he had possibility to quickly develop the SA with the ad hoc engine-oriented system in order to identify the problems and give advice. However the captain involved was completely out-of-the-loop yet supposed to make the final decision. The scrutiny of captain’s SA development device via activity theory (Kuutti, 1995) reveals a “role shift” on the operator with a new task of orienting the captain. The original task was to monitor the unmanned vessels with the HMI in normal situations, but if the captain was involved for critical situations, the operator’s primary task turned to get the captain into-the-loop as his “sense making tool” (see Figure 14).

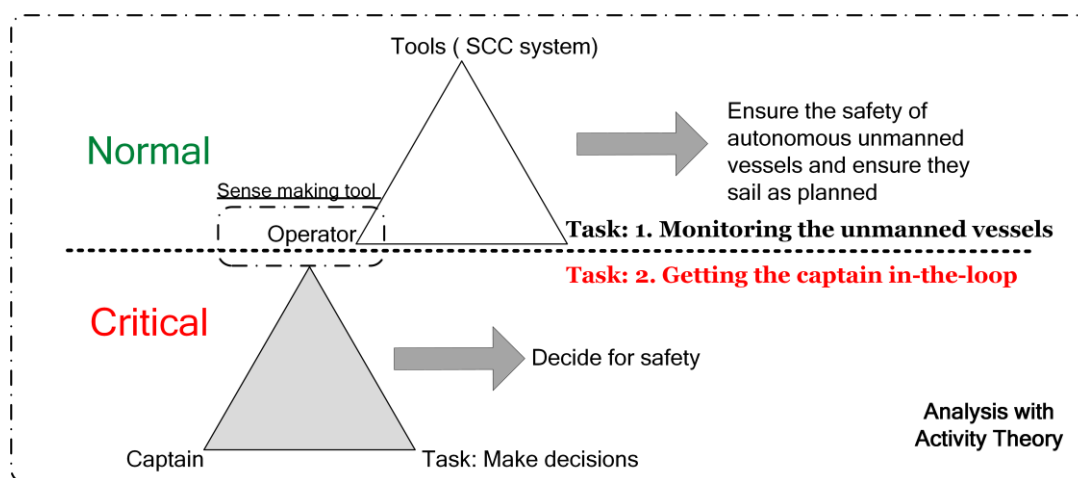


Figure 14. The operator’s “role shift” in the analysis through activity theory - from a system supervisor to the captain’s sense making tool

Literally the captain became the Team SA chain's weakest and most vulnerable link when he had difficulty developing SA about situation. A possible explanation is that the prototype HMI is incapable of supporting efficient SA transfer among team members and this result in the heavy reliance on the exclusive SA Device, i.e. the communication, for the development of the captain's Shared SA. This is unlike a watch handover on a vessel, but occurs during a period where the operator is likely uncertain of the data, the situation is complex or a time pressure has been introduced, possibly bottlenecking the decision making process. Human performance is something that highly depends on the situation and context that exists at the time events occur (McLeod, 2015). These are not circumstances that likely facilitate consistent and complete SA transfer. With the total prolix procedures to go through, this hierarchy and assumption of the regulations introduces unreliability and inconsistencies which in return impacts the overall system performance. It suggests a fundamental need to conduct Cognitive Work Analysis (CWA) (Rasmussen, 1986; Salmon, Jenkins, Stanton, & Walker, 2010; Vicente, 1999), to address the data processing strategies and available resources for each phase of decision sequence involved in a supervisory control task. Particularly in the CWA framework, Social Organization and Cooperation Analyses (SOCA) would look into what and when coordination is necessary among human agents at which phase of the task (Vicente, 1999), how technology artefact could support with the human-human cooperation by supporting their task processing strategies. These are the theoretical underpinnings of a robust HMI design that can support team members to work in a coordinated fashion and completing complex supervisory tasks effectively and efficiently.

By following the discussion about organization and cooperation analysis, we are approaching to a key question on the skill set of team members and pedagogical issues in this futuristic concept of a "SCC and Unmanned Vessels". What we realize is that the concept of a SCC still must evolve that the SCC is neither a shore-based bridge nor an evolution of Vessel Traffic Services. The SCC may be more aligned to the aviation industry: Would an aircraft pilot make a suitable air traffic controller? Why is an air traffic controller educated differently from a pilot? Are the skill sets of a successful air traffic controller the same as those of a pilot? It needs to address the competencies of an ideal worker with respect to the design strategies and approaches in the phase of Worker Competencies Analysis (WCA) in CWA (Vicente, 1999). Rasmussen (1986) claims that in the process of HMI design, "the design of a training scheme matching the requirements of the cognitive tasks must be considered" (p. 59).

The discussion on perceptual factors, cognitive factors, environmental factors, and organizational factors in terms of individual and Team SA development process provides a very important indication on the concepts of HMI. The design of HMI is not a simple matter of constructing graphical user interface as it was usually referred in the industry. What must be emphasized in our HMI considerations is that the system shall not only support data transfer and visualization, but also the process and context in which data are perceived and understood for consensus decision-making. It is highly recommended to take them into account thoroughly via a holistic systematic approach in order to really support the human agents to achieve high level of understanding of what is going on.

5.2 Automation Bias in HAS

In a SCC, the dashboard integrated with the six vessels' status is a typical decision support system for an operator to detect the anomalies, understand the situation and make decisions. When an alarm is triggered due to a deviation from the predefined operational threshold, the sound and visual form of the alarm directs the operator's attentional resource to the abrupt change in the system while the suggested diagnostic messages on the screen pose higher cognitive demands upon the operator in the interpretative process. Though the operator seems like a receptionist in the organization, but his actual role is more closed to the manager of this networked cognitive systems as the trend of the operator's role shifting indicates in Chapter 2 (Boy, 2011). If the pre-programmed knowledge-based decision support automation fails to recognize the situation, he is supposed to investigate the situation himself to resolve the issue. For example, there could be engine alarms with explicit suggested diagnostic messages such as "fishing boat in vicinity" or "pump injection failure", but there could be also implicit messages such as "unidentified object detected" or "engine abnormality detected" due to the automation's failure to recognize the pattern. Within a highly automated decision making support context like this, the overall performance of the safety-critical system can be severely influenced by the automation reliability and how the human operator utilize the automation technology. The grounding of ship *Royal Majesty* is a perfect example of ill-designed automation and biased use of automation (Lützhöft & Dekker, 2002; Parasuraman & Manzey, 2010). The studies in the context of the MUNIN project would also focus on the interactive relationship in a HAS and the factors that could contribute to the effect of biased use. It might be a truism to discuss complacency and automation but one of the prominent issues this study needs to address is automation-induced complacency and automation bias in a remote supervisory system which is inherent in HAS (Sheridan, 2002). The aim is to gain insights upon the automated decision support tools, particularly alarm management system design that should be tailored to the contextual constraints, task needs and human operator's limitations.

Complacency originates in the aviation sector as a contributing factor to accidents that it primarily refers to the operator's purported behaviour of not conducting necessary system check but assuming "all was well" when the dangerous situation actually evolves (Parasuraman & Manzey, 2010). The essence is over-reliance on automation and causes automation bias - "the errors resulting from the use of automated cues as a heuristic replacement for vigilant information seeking and processing" (Mosier et al., 2001; Mosier, Skitka, Heers, & Burdick, 1997, p. 47; Skitka et al., 2000). The two outstanding categories of automation bias, "errors of omission" and "errors of commission" (Skitka et al., 2000) were both observed from the simulation trials in the SCC: the operator failed to respond or delayed responding to the systems irregularities (error of omission); the operator trusted the prominent parameters on one display despite contradictory information on other (error of commission). The results from the gap analysis directly ascertained the circumstances of error of omission that the alarm got delayed / didn't come at all. It is very likely the software programming bugs, causing inconsistent data display on the different monitors, resulted in several observed errors of commission. Beside the reliability of the software programme, automation delay or failure is mostly due to the delay caused by the volatile quality of network connection and inappropriate alarming threshold

configuration. Firstly it could take a considerable amount of time for the data from the field to transfer to the operator. When receiving a critical alarm the out-of-the-loop operator is confronted with high stress. The threshold configuration for the supervisory system should consider leaving the operator some time buffer to get into-the-loop. In real-life, the data probably will be transferred via the satellite link instead of totally depending on the internet in the lab trials. It means that the delay is also an important factor to the system's reliability and resilience that design needs to take care of in the most elegant fashion. All these manifest the critical role of automation reliability.

But In the simulation trials, we also have seen that the operator was very busy with checking status of another unmanned vessel and missed the alarm. In such cases it suggests the importance of procedures and workload regarding automation bias. Although the operators were informed about the possibility to relieve their workload by reporting the “resource allocator” in the SCC (i.e. the supervisor), the handover protocols were quite flexible in the first place. One of the operators even revealed that he would rather bear a relative high workload for a reasonable period of time instead of leaving his superiors an impression that he was incapable and not accountable for critical situations. It seems that it is the “accountability” that drives the operators to make errors in a very stressful situation, preferring trusting the salient data instead of involving more actors for a “double check”. Skitka et al. (2000) proposed that accountability can lead to “greater cognitive complexity” and “improved human judgment” to “reduce the tendency to make errors of omissions and errors of commission”. However, with the implicit regulations and vague description of job duties introduced in the sociotechnical system, this factor paradoxically resulted in more opportunities for automation bias. In these cases the operator usually failed to allocate the attentional resources at the right places at the right time.

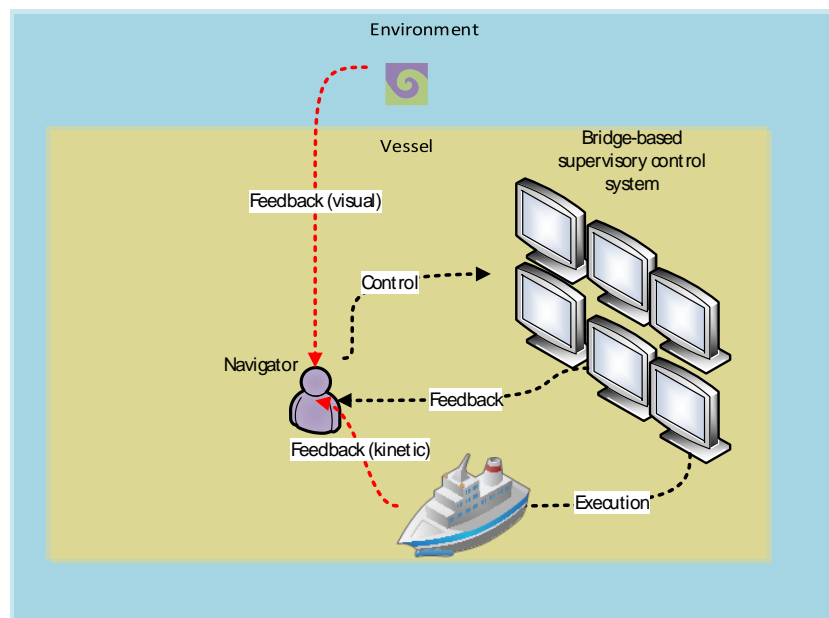


Figure 15. Centralized supervisory control with ship-sense onboard

A deeper reason is found after a careful scrutiny of such paradoxical effects of “accountability”. Skitka et al. (2000) hold the proposition that errors of omission are the result of cognitive vigilance decrements. It might be the case for monitoring the vessel onboard because the navigator has substantially various options to detect the system irregularities (i.e. ship-sense) and verify the information. Except for checking the parameters from the bridge-based control system, the navigator can also directly perceive the information from the environment and feel the kinaesthetic movements of the ship. Even with presence onboard, the problem of mental isolation and physical isolation (Norman, 1990) still exist due to the high degree of centralized automation in the field (see Figure 15). Without sufficient cognitive vigilance to view surrounding environment and other sources of information, the inherent isolation effect could lead to typical automation bias, as it is indicated in the grounding case of *Royal Majesty* (Lützhöft & Dekker, 2002).

However vigilance seems to become a less paramount factor onshore because the partial “sensory deprivation” (i.e. lack of presence) results in the intrinsic contextual incapability of detecting system irregularities through other information channels. It also greatly effects the operators to make errors of commission: it is not the case they have a belief in the superior judgement of automated aids or does not want to check more reliable sources of information but they are unable to verify the information by contrasting what they read on the screens with what is actually going on in the field. Though the SCC looks like a centralized supervisory control system, the whole system architecture is rather distributed, with a data communication channel to link the control platform SCC and controlled process in the autonomous unmanned vessels. Figure 16 abstracts the system hierarchy in the form of remote supervisory control. In such a unique HAS structure, the key influential factors of automation bias is the contextual constraints which greatly hinder the human agent to conduct early detection of the irregularities but more or less be forced to over-rely on the automated system and follow the whatever salient cues in the interfaces.

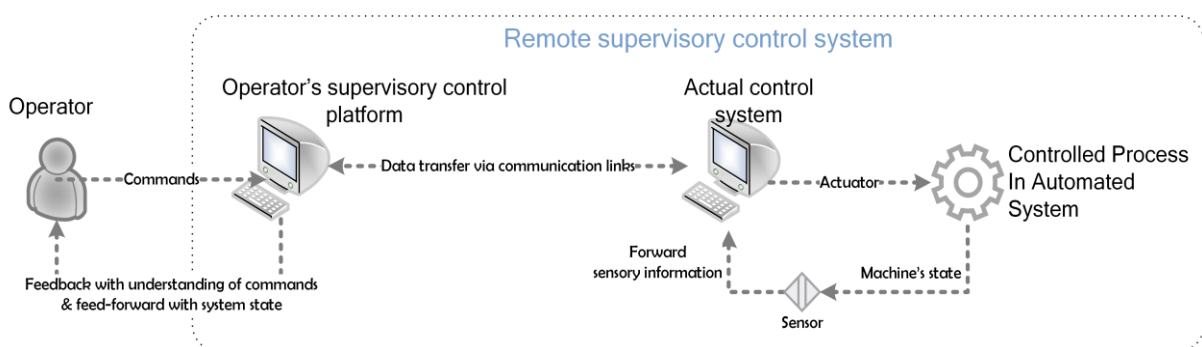


Figure 16. Remote supervisory control system

Essentially more layers of complexity in a remote supervisory control system. The operator’s supervisory control platform not only needs to give feedback regarding the command by the operator in real time, but also the system state or mode based on the sensor data. The distributed characteristics increase the variability in the system and shifts much of the reliability of whole system on this control platform from the proximal end which acts as a “gate”. The HMI of the

control platform needs to interpret the raw data from the distal end and present it to the operator. If automation runs normally, the operator would gradually turn complacent and monitor the situation in a passive pattern, which does not necessarily bring hazards to the system itself if the automation keeps running normally. This partially explains the positive feedback on the participants' subjective SA assessment questionnaire and debriefing. However, if automation runs abnormally, the operator has no other options but to do a visual scan through the screens. Just as it was indicated in the empirical research done by Chen, Barnes, and Kenny (2011, p. 371) that "participants' attentional control impacted their overall multitasking performance", the operator's attentional resources would be directed by the attentional bias from the interface such as the alarms and those implicit messages in the HMI. The robustness and consistency of the HMI would have a direct impact on the operator's ability to perceive information and achieve high level of understanding in the closed automated environment of the SCC. With these contextual constraints, the discussion about HMI regarding automation bias is quite consistent to the previous discussions about SA that the tool serves as a vital SA development device in the process during which the operator himself could hardly get other information resources and be likely prone to automation bias. In order to cope with complexity and variability, the HMI design of a remote supervisory control system with distributed situated structure cannot ignore the extremely important role of context. It shares a similar view of Parasuraman and Manzey (2010) that automation bias is more than a decision bias but much dependent on the attentional processes which could be significantly influenced by the overall context. In this closed automation environment, distributed from the situation, the attentional effect becomes a predominant factor pertinent to automation bias instead of vigilance or accountability. A reliable automated decision support HMI should quickly allocate an operator's attentional and cognitive resources by providing logical affordance with regard to the overall system status and specific abnormality.

The logistical and tactical grouping of data must also be considered in the interface so the automated decision aid could navigate the operator towards the true problem and underlying causes. For example, salient cues about the six vessels' modes and the automation status indicators (i.e. flags) on the top layer of the interfaces is provided to enable the operator to quickly check the overall performance of the system. This speeds up their efficiency to get into-the-loop. When an operator clicks a certain alarm on the dashboard of one specific vessel, all other screens (the electronic sea chart, radar, conning display) are synchronized to show the detail information of that focused vessel in a consistent manner. This actually avoids demanding more cognitive resources for artefact-metaphor mapping. What can be further improved is that CPA (Closest Point of Approach) and TCPA (Time to Closest Point of Approach) could be highlighted on the display in case of collision avoidance alarm, to reduce the cognitive load on searching and data verification.

Through the discussion of automation bias in an HAS, it is approaching the essence of one "good" automated decision aid tool. A decision aid tool's task is not to make the decision for the operator because human operator is still the unique decision maker in the whole system. With the prevalence of imperfect automation today and maybe in the far future, the more exact

decision it made for the user (e.g. initiate a collision avoidance protocol), the higher risk of automation bias it might introduce. A decision aid tool's task is not to present all the information that system collects and throw it away to the operator for him to scrutinize in an "unbiased" way, because by giving decision aid, it is already some sort of automation bias anyway. In such a remote supervisory control system, the unreliable long-distance data communication link, the complex automated process, and inherent lack of presence would certainly affect the reliability of the automation. As a matter of fact it is challenging to design a purely reliable automation in any existing HASs. The design should consider the fault tolerance of a HAS and "look for the best trade-off between the positive and negative effects" (Alberdi, Strigini, Povyakalo, & Ayton, 2009) rather than eliminating all of its uncertainties. The discussion on automation bias is pertinent to some fundamental mechanism of human errors. This is the point where the traditional thoughts consider that it is a purely usability issue in HMI design or because of insufficient training. In fact there are recent studies examining how experiencing high reliability in training could lead higher levels of complacency and automation bias during operational conditions, but also discovering the limitation of training to reduce complacency and automation bias (Chavaillaz, Wastell, & Sauer, 2016; Sauer, Chavaillaz, & Wastell, 2015). It implies that errors cannot be totally removed through well-designed HMI or training programmes but their effects could be mitigated by introducing an adaptive design of automation to meet the dynamic cognitive demands of a highly automated system. Adaptive automation should be way beyond "taking over tasks only when operators are overloaded but give them back to them when workload is lower" (Skitka et al., 1999, p. 716), as the automated decision aid tool's ultimate objective is to integrate the automation in the context with the complex cognitive mechanisms in sense making under uncertainty, so that it could dynamically "walk" the operator through the problem identification and decision making process as well as support recover from disturbances and errors.

5.3 Ecological Interface Design

The thought of coping with human errors and supporting problem solving by a proper design of an adaptive HMI is quite compatible with principles from the theoretical framework of Ecological Interface Design (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992), which is grounded on Shneiderman (1983)'s *Syntactic-Semantic* model of Direct Manipulation Interfaces (DMI) and Hutchins, Hollan, and Norman (1985)'s *Distance* model regarding the feeling of "directness" in the interfaces. Based on the cognitive requirement in terms of gulf of execution and gulf of evaluation (Hutchins et al., 1985; Norman, 2013), DMI allows the operator to act on the representation mapped from the real world and receive feedback immediately. The "distance" gets shorter and fewer cognitive resources and efforts are required to diagnose and solve the problem. Consequently mapping of domain objects of interest to the interface in a way that matches the operator's cognitive control pattern is a theoretical approach to make the HMI "psychic" enough to be able to "walk" the operator through problem solving processes.

5.3.1 Ecological Representation as the Spirit of HMI

EID delineates the mapping activities at the skill-based, rule-based, and knowledge-based levels of cognitive control, so the representation of the ecology could be tailored in accordance with the requirement of information processing at each level (Rasmussen & Vicente, 1989). From the perspective of decision ladder (Rasmussen, 1986), the essence of EID is to the map abstract properties of the internal process to be controlled or the work domain constraints to the salient cues in the interfaces so it supports direction perception of the original invisible machine status and process constraints as well as direct manipulation of conducting actions directly on the system in skill- and rule-based level (Bennett & Flach, 2011; Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992). From the perspective of Gibson (2014)'s theory of perception, this mapping process of the invisible task or work domain constraints is to transfer the *invariants* in the real world to the *invariants* displayed in the interfaces in a way that the affordance can “naturally” manifest goal-directed action aids to the operator with regard to the constraints from the ecology (Rasmussen & Vicente, 1989). In addition, EID intends to interpret the information symbolically in knowledge-based level and “display the process’ rational structure directly to serve as an externalised mental model” (Rasmussen & Vicente, 1989, p. 530) to support learning adaption and decision making in complex systems.

Although EID have been applied in various fields, such as process control, aviation, software engineering, the visual perception for display design is the major application (Vicente, 2002). In the simulation trials of MUNIN, the findings reveal the out-of-the-loop risk and subjective perceptual difficulty to detect and identify problems as efficiently as done onboard. The model of *Distance* and ecological mapping enlighten us to see how the representation of the distributed situation in the interface can match a user's mental model is pertinent to the feeling of presence as well. It suggests the opportunity and value to consider mapping the properties of certain controlled process and important environmental constraints to HMI in other feasible modalities rather than merely as a visual channel. Such representation is propagating presence in nature and creating the virtual ecological environment by mapping the *invariants* of distal context (e.g. ship-sense) to the proximal HMI (e.g. vibrating chair or Virtual Reality Headset). Computer mediating technologies could be considered to create such affordance for the supervisory controllers to get into-the-loop at a quicker rate. It might likely increase the operator's ability to validate other source of information received from the display and maintain high level of SA to understand the situation and act in the goal-directed manner. Our interpretation of mapping expands the scope of creating the virtual ecology to enable direct perception and manipulation, which could likely significantly shape performance of decision making and problem solving.

In the case MUNIN, it has been also frequently observed that the participants are making their own inference based on their existing experience, like the discussion between the operator and captain about the manoeuvring strategy described earlier in this chapter. Although they are all master mariners with considerable navigation experience and may have encountered similar situations in real life, there is still interference in the decision making process that almost lead to collision at sea during the simulation trial. The lack of the spatial-temporal cues regarding the target unmanned vessel's position in relation to other vessels in vicinity is seemingly the

plausible explanation, but the deep reason might be situated in the imperfection of the HMI to adapt to the development of an operator's mental model in such a new task environment by providing a systemic picture of the problem and constraints (e.g. the safety concerned functional properties of the system). In unfamiliar task environments, it is rather important for decision support system to support operators in adapting changes and unanticipated situations to be really usable in practice (Vicente, 2002), as none of the participants had ever conducted remote supervisory control upon autonomous unmanned vessels onshore and none would ever know how the manoeuvring should be perfectly done to avoid collision in case of abrupt automation failure. The operator and captain share the same goal to ensure the safety of the vessel, while they have different approaches to achieve this goal. One important reason that they choose differently is that their existing experience in similar cases differs, and this would make them prone to inadvertent actions without considering other important constraints from the ecology in an unfamiliar task environment. Decision bias, automation bias, procedural traps, out-of-the-loop, these are not the cause but the effects of an opaque system, where the representation of the problem in the work domain and the constraints in the overall context fail to resonate with dynamic development of an user's mental model and decision making process. This is quite consistent with the idea from EID that HMI should provide the users resources for identification and prognosis as a goal-directed structured process of externalizing the mental model (Rasmussen & Vicente, 1989).

That provides a very important indication about improving the transparency of the complex HAS. HMI should make the hidden complex control objects and their tangling relationship visible in a goal-directed structure for a user to manipulate, and that is how the mapping should be done to make the system become real transparent for analysis and planning. When the operator detects an abnormality, his duty is essentially about diagnosing the system's problem, figuring out the state of the machine, and make decision about how to select approaches to correct system disturbances. Knowing the internal functional structure of automation is important for a supervisory control decision maker to see link of cause-and-effects across various levels and therefore understand the state of the machine by realizing how disturbances and events are propagating through the system. This is a basis for the decision making and planning in the knowledge-level of Rasmussen (1987)'s cognitive control model. As a diagnostic search aid tool, the design must construct a logical representational structure of the system in a compatible way in order to optimize the use of operator's attentional resources and provide decision making support. For example, a means-ends or goals-means "abstraction hierarchy" is such a structured methodological tool to represent functional properties of a system, consisting of five levels of abstraction: functional purpose, abstraction function, generalized functions, physical functions and physical forms (Rasmussen, 1986).

This is also applicable in the automated supervisory shore-based system in the MUNIN project. At a higher level of the representation, it can be designated to take care of specific aspects of the system, i.e. engine, cargo or SCC itself; in the middle levels, there should be organized structure of the complex automatic functions, their interrelations and effects, operational range and scope, so the aggregated indicators of the system status could emerge and stand out while

alarm indicators could be seamlessly embedded in the interface design; at the lower level it should keep track of physical properties and even non-functional constraints that are hidden but across all modules in the distributed system, such as the intrinsic dual communication delay that would probably to certain degree impact their decision making performance.

In the MUNIN prototype, both top and bottom up approaches are necessary in the construction phase of ecological representation. A top down approach is looking at how purpose or objectives could be implemented by functions or physical components, like how the mode of automation is reflected by the top flag, which is influenced by key indicators aggregated from lower-level automation properties and contextual constraints. The bottom up approach is looking at how physical components and functions could serve or influence purpose, like how the delay in the infrastructure could influence the dynamic situation at hand, and how “pump injection failure” could influence the manoeuvrability for task of collision avoidance in case of automation failure. This is essentially a process to outline the “spirit” of the HMI, as it was described as externalization of mental model (Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992).

There is also an important indication in engineering implementation that structuring the representation in the database could be considered in the development of knowledge-based decision support systems. However we should always understand it is the resources the system shall provide instead of the plain decision. After all, it is the human operator who makes the decision. With the provided resources for decision making, the operator has the possibility to dynamically adapt to unfamiliar situations efficiently in complex systems, even in the irregular situations that the designers might never think of during the design phase.

5.3.2 A Focus Shift on Situation Awareness

Grounded on the theory of EID, Bennett and Flach (2011) propose the triadic semiotic system, consisting of *Matter* (i.e. ecology), *Interface* and *Mind*. The success or failure of the interface design is no more the matter of interaction between the operator and user interfaces as it has long been recognized in a dyadic ontology of the traditional HCI discipline. Our discussion so far has revealed the common ground shared with EID - the success of the interface is also significantly influenced by the characteristics of the task situated in the field, or the constraints from the overall context. For example, it is meaningless to evaluate the interface design without recognizing the huge difference in the context when moving people from ship to shore, when the onboard cues disappear in an office-like environment. We argue that the true success of the HMI design is pertinent to the interaction between the user (awareness) and world (situation) via the mapping representations and reflected actions through the interfaces, so is failure. This seems to be consistent with the term “situated action” introduced by Suchman (2007) that “every course of action depends in essential ways on its material and social circumstances” and “people use their circumstances to achieve intelligent action” (p. 70). From this perspective, the goals are associated with the dynamic environment and circumstances in the working field rather than merely being something between ears.

But is it contradicting the dyadic interpretation of Endsley (1995b)'s SA model that seems to follow the old-fashioned information processing paradigm? SA is traditionally interpreted as something situated and developed through a data-driven information processing stages in the mind (Dekker & Hollnagel, 2004), which Endsley (2015b) believes is usually a misconception and misunderstanding towards its goal-directed non-linear essence. However, Flach (2015) points out the inclusion of impacts from system factors (e.g. complexity, automation, etc.) and individual factors in Endsley (1995b)'s *model of SA in dynamic decision making* is a strong evidence of its existence in forms of the triadic semiotic system of *matter*, *interface* and *mind*, which might not be consciously recognized by Endsley herself. But still, SA model and EID advocates the importance of context as the premise of reliable system design.

This gives us the opportunity to see the combination of the formulation of awareness with the development of mental model and the contextual complexity of the situation in the ecology as the theoretical underpinnings of HMI concept. On one hand, HMI serves as an intermediary to transfer the physical forms and relationship of controlled objects in the real world to a subject's awareness. This is an adapting process of completing the mental model and goals (e.g. formulation of sub-goals, adaption of situation by choosing an appropriate method) and thus directing the attention to specific aspects of the situation (e.g. constraints in the context). On the other hand, the HMI transfer the "situated actions" from the subject to the controlled process, to the controlled objects of the world, and shape their physical forms and relationship in a way that the subject's goals and cognition is sort of "situated" in the transition of properties of the substance. From the perspective of a philosophical ontological doctrine, the previous assertion is partially against idealism that the worldview is dominated by the belief that objects are ideas that only exist in the mind (Guyer & Horstmann, 2015), while the latter assertion is partially against the materialism in which matters exist independently of thoughts (Marx & Engels, 1845). Bennett and Flach (2011) believe the radical empiricism constructed by James (1976) could well address the problem of the dualism by the introduction of concept of pure experience to eliminate the substantiality of substance and consciousness. They claim that human experience is the essentially the joint function of mind and matter (p. 460). This stance shares some common ground with the idea behind Hollnagel and Woods (2005)'s Basic Cyclical Model (COCOM), that "meaningful human action is determined as much by the context as by the inherent characteristics of human cognition" (p. 16). The concentration on human experience implies the intention to unshackle the chains of other late-developed principles on human factors but embrace the original existence of experience based on the theory of being or ontology. The radical empiricism as metaphysics shed light on the existence nature of HMI that HMI serves as intermediary artefact to connect the particulars of *situation* and *awareness* to complete the human machine interaction in a manner of reciprocation, resulting in the formulation of new forms of *situation awareness* in the mind and in the wild.

With the prevalence of complexity resident in an automated system, operational tasks, and cognition, a shift from the traditional belief of SA that it is all about studying cognition in the mind to an extra wide-scoped belief on the functions of SA in the sociotechnical system is a must in order to address the complexity and uncertainties. Of course this does not mean the

research on the communication between human and an interface should be deterred by notions of “cognition in the head”, as the exploration in the internal process to perceive and understand is as important as the exploration of ecology. We would rather prefer a combined approach to learn the complexity of the world. The paradigm shift trend of cognitive system from structuralism which primarily focuses on what happen inside *an agent* to functionalism which primarily focuses on what happen inside *a system*, indeed provides us opportunities to reflect and ponder the conflicts and contradictions in dialectic of philosophy, so a profound understanding with a dynamic and development vision can be achieved.

5.4 Sociotechnical System: HMI for Decision Making, System Resilience

While more and more efforts have been spent to describe better integrated analytical approaches or broader frameworks on this well-trodden cognitive system engineering path to bring better system performance in a sociotechnical system (Hollnagel & Woods, 2005; Rasmussen, Pejtersen, & Goodstein, 1994), we should not forget why we are on that path and the importance of the domain in the first place. In a human-technology context, the operator would still likely remain to be the “final barrier” (or “last straw”) in the maintenance of a system. HMI has a pivotal role situated in the core of the interactions among various system factors in the system being controlled. Vicente (2002) points that “any interface will not realize its full potential unless it is implemented as part of an integrated approach to system design” (p. 74). A sociotechnical system’s perspective usually provide such systemic views to designers to fathom the work field, the domain, independent of the concrete realization form of automation technology being utilized in the system.

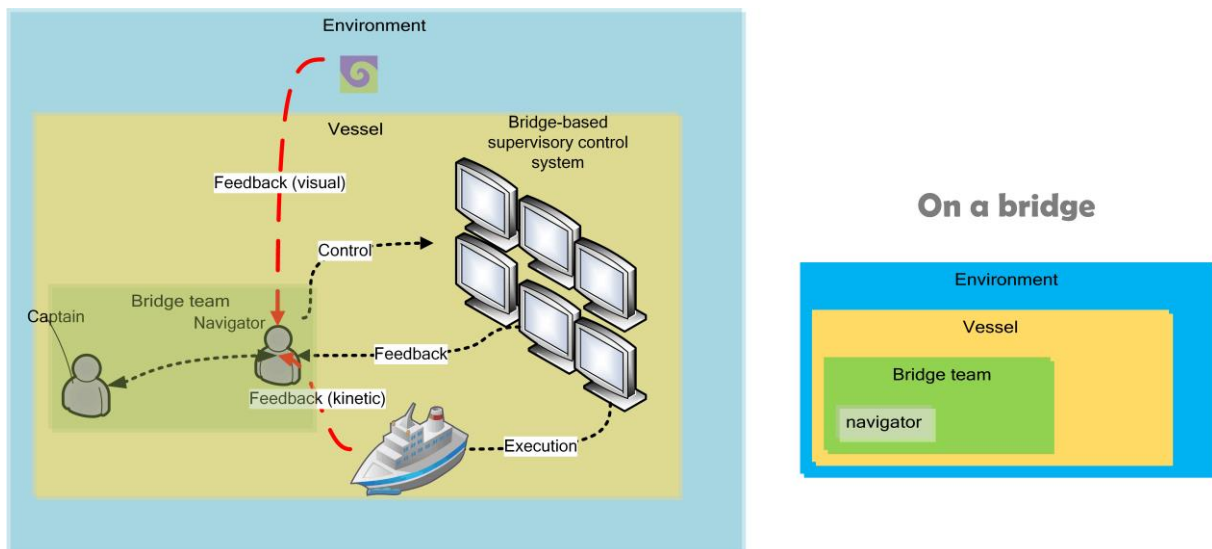


Figure 17. An instance of a centralized sociotechnical system onboard

Ships can be considered as a combination of technology and a social system (Grech, 2008). The “Integrated Bridge System” (IMO, 2002) serves as a supervisory control system to provide navigational and meteorological services and warnings which is jointly used by the bridge team.

The navigation activity is considered as one complex joint activity that highly depends on both individual and team performance, tools and technologies, diversity in geographic and hydrographic features along with great variability in operating conditions (Forsman, 2015; National Research Council, 1994). Presence and supervisory system co-create a centralized experience of ship-handling for the situated navigator (see Figure 17).

The MUNIN project has revealed another system picture (Porathe, 2014; Porathe, Burmeister, & Rødseth, 2013). One important question that has been raised from the beginning of the project is the feasibility of reallocation of these existing system components in a distributed pattern to satisfy the functional requirements of the operators and even the entire organization. It was assumedly plausible to prototype a mimic of the ship bridge onshore based on the conjecture that there might be considerable task overlap between an officer of watch on a bridge and an operator in a SCC. The envisioned distributed sociotechnical system is illustrated in Figure 18.

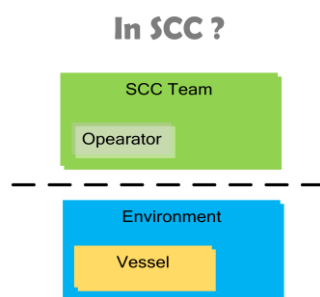


Figure 18. The envisioned distributed sociotechnical systems in the case of MUNIN project

Results and previous discussion suggest that creating a reliable distributed sociotechnical system is way much more complicated than merely reallocating system factors extracted from a centralized sociotechnical system in a distributed manner. The main challenge is that an operator is basically interacting with a *grey box* to perceive partial representation of the geographically remote field. The effect of partial “sensory deprivation” with opaque HMI is insufficient individual and team situation awareness. The observed inadvertent actions, or “non-situated actions”, are reflecting the automation-induced bias fostered by the mental isolation compounded with exacerbated physical isolation in a distributed highly automated system. The concept of implementation of a SCC by reallocating a bridge system to the shore side and fine tuning can hardly be called as a success. Nevertheless, a deeper understanding towards the sociotechnical system pertinent to HMI design is gained, as it is outlined in the synthesis of Human-Human Interaction (HHI), HCI and Machine-Machine Interaction (MMI) in Figure 19.

It is important to realize that a HMI’s ecological mapping capability and its transparency is a vital factor to dynamically influence individual and even team situation awareness and mental model development. A decision support system shall not intend to inform the operators the decision to make, but support and inspire them, through the two-folded process - the cognitive process by affording diagnostic resources and disturbance-absorbing reversibility as well as the physical perceptual process by mediating presence in a distributed environment. From the functional perspective HCI remains to be the centre of the whole HAS, but it is not an indication

of technology-centred paradigm. It is a use-centred one instead, which has two indications: 1) the user and the computer are the equal agents in the system. Their meanings in the system are represented as the interaction pertinent to the system goal or purpose. 2) Optimal experience in HCI shall be the basis of overall reliable system performance in use across different formalities of interactions in the overarching system. In addition, adaptable technologies need to be flexibly considered in the design phase to balance the trade-off between cost and benefit and elegantly address the delay issue in the distributed sociotechnical system.

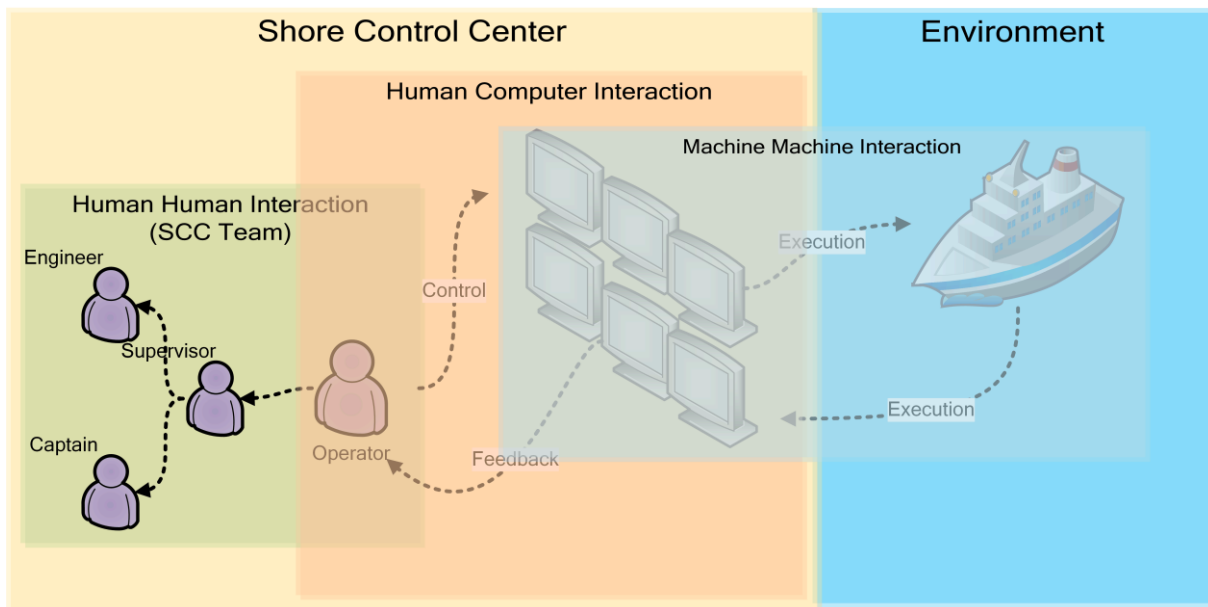


Figure 19. A synthesis of Human-Human Interaction, Human-Computer Interaction and Machine-Machine Interaction in a distributed sociotechnical system in the case of MUNIN

While technologies are progressing in a credible speed with an exponential growth curve to approach a seemingly revolutionary singularity after 30 or 40 years from now on (Kurzweil, 2005), operators will remain to be the same operators and supervisory tasks remains to be supervisory within a rather long time span. 45 years ago, Apollo 13 failed to land on the moon because of the oxygen tank explosion, but the astronauts and operators used their imaginations and resources in the system to quickly adapt to the unanticipated situations and successfully fit “square pegs in a round hole” in a lifeboat to get back to the earth successfully. It is classified as most well-known “successful failure” in history of NASA (2009). The rescue operation involves considerable amounts of teamwork between space and base, in a distributed fashion as it was in the case of the MUNIN project (except it is human automation cooperation from a distance). In the MUNIN context, when a situation goes pear-shaped, the teamwork in the SCC needs to solve the problem and even may improvise if it has to. In previous discussion we have reflected upon the pedagogical gaps, organizational structure and its functional requirements in a distributed context, where HCI design cannot sidestep. What’s more, the design of training programmes and organizational hierarchy has to accommodate the distributed characteristics of the sociotechnical system and allows human agents with different backgrounds and competence to perform teamwork in a coordinated and resilient manner. CWA (Vicente, 1999) could be a

useful analytical technique in the early phase of design. That is a fruitful lesson we learnt about integrated system design and system resilience.

Admittedly it is still far from constructing a well-rounded HMI know-how to cope with the complexity and uncertainty just by scrutinizing a more or less semi-failed prototype in an EU project. However, these accumulative considerations throughout the whole thesis provide everyone a basis to appreciate the complexity of the HMI concept and prompt us to reflect upon its connection to the sociotechnical system design in a wider scope. From this perspective, this study regarding interfaces could be fairly considered as another experience of “a successful failure”.

6 Conclusions

The focus of the study is to address the emerging issues during the integration of human and technologies in a wider scope instead of anchoring to the heuristic of “human observer – interface artefact”. Thus the design can truly support human agents to dynamically adapt to the variability and contingencies in a complex system. This could be considered as a process of thinking out of the traditional dualism box of HMI concept in which the belief is interface and human are isolated entities, despite the fact that different HMI designs could significantly influence the performance and experience of a human operator.

In this study, investigations about how the distributed properties of the system could influence HMI design, in order to explore what composes a reliable decision support HMI to facilitate human element for problem solving. Experiences from the MUNIN project regarding remote supervisory operations towards the controlling of unmanned autonomous vessels provides an example of an HMI structure and a contextual background to delve into the design explored in this thesis.

By systematizing the centralized situation aboard from the sociotechnical system perspective as a starting point, it suggests that maintaining high level of SA could become an unprecedented challenge for HMI design used in MUNIN, such a highly automated distributed context. While the ability to quickly verify and validate information regarding the automated process is considered as the necessary means to remain in-the-loop and achieve higher levels of SA in a centralized HAS, the lack of the presence in remote control environment hugely constrains an operator’s perceptual channel and consequently degrade his adaptive capabilities. Without a transparent HMI to address such systemic changes, the effect of increasingly higher degree of automation would likely result in more human errors by using automation in biased ways. A HMI must take into account how the constraints in the context could be represented in the interface to influence an operator’s perception and attention. With the exploration on mental model and automation bias, a deeper understanding of human error and HMI is gained: the opportunity for a human to make an error cannot be totally removed through any “perfectly” designed HMI or training programme but their effects could be mediated in a design framework towards system resilience. The design needs to accommodate the perceptual or physical attributes of controlled process and the cognitive attributes of the operator so it allows him to cope with the complexity of the world in an adaptive goal-directed manner. It is essentially a process of integrating complicated automation in the field with the complex cognitive mechanisms of the human agent. To truly support the operator’s high level of understanding and decision making, the design should include transparency in the automation representation and derive resilience from a fault-tolerant design thought to cope with disturbances and errors. Errant mental models and low level of SA might not necessarily jeopardize the performance in a certain period of time but stagnation may so erode performance. This prompts the focus of HMI from a narrow angle of individual awareness to a wide angle of complexities of ecology and resilience of the system.

EID is a deliberate but quite consistent effort to clarify how the transparency and resilience of the system could be addressed in the HMI with the ecological thinking. The *flesh* of an adaptive decision support HMI is the proximal mapping representation of the invariant in the distal ecological context in the interface, while the *spirit* is the logical representational structure of automation as an effective means of developing the operator's mental model. The HMI design should virtually reflect the ecological reality on the account of human operator's cognitive control mechanism (e.g. SA development phases, or the three-level control behaviours). This enlightens the engineering implementation of a knowledge-based decision support system to be conducted in a proactive and resilient fashion. The reflections upon ecology have significant meanings on the notion of SA, which has long been widely interpreted as "cognition in the head". HMI serves as intermediary artefact to connect the particulars of *situation* and *awareness* to one united form to complete the reciprocal human machine interaction, resulting in the formulation of new forms of *situation awareness* in the *mind* and in the *wild*. With the prevalence of complexity resided in the automation system, operational tasks, and cognition, a shift from the traditional belief on SA that it is all about studying information processing in the mind to an extra wide-scoped belief on the functions of SA in the sociotechnical system has emerged to learn the complexity of the world.

In addition, these studies have also reflected the design from a sociotechnical system's perspective. The results on the Shared and Team SA suggest the huge impact from HMI on the SA flows between each individual within a team. Activity theory is utilized to understand barriers in teamwork due to an ill-designed HMI that sidesteps the underlying organizational factors, such as team settings, optimization of teamwork process and organizational hierarchy. This implies the importance of cognitive work analysis in the early phase of design, which should be incorporated to the HMI design concept as an indispensable part of sociotechnical system design. The design of training programmes and organizational hierarchy needs to accommodate the distributed characteristics of the sociotechnical system and allow human agents with different backgrounds and competence to perform teamwork in a coordinated and resilient manner. The HMI design for system resilience is a practice beyond graphical user interface design for data display and visualization, but a dialectic philosophy of design for use experience adaptively in a sociotechnical system in which information is perceived, shared, understood for consensus decision making.

7 Future Work

Alarm is an announcement to the operator initiated by a process variable or measurement passing a defined limit as it approaches an undesirable or unsafe value (Rothenberg, 2009). In the context of MUNIN, the dashboard system in the SCC is an aggregated alarm system with major focuses on clustering big chunk of ship data and seamless integration of traditional navigational techniques. However, for conventional alarm systems employed across various industries, the complex tangling relationship of alarm constraints and higher degree of automation has long increased the complexity of diagnostic procedures and decision-making process. The complexity of automation and control has shaped the operator's investigative practice from a printer technician's creative examination activities followed by highly-skilled improvisations described in Orr (1996)'s ethnography. Operators get stressful, confused or forget the alarms in nature which have been silenced earlier (Hollifield & Habibi, 2011). The transparency of a system doesn't necessarily improve just because the operator is geographically situated in the field – generally the alarm management system remains to be a “grey box” of automation. It is critical to organize the technology in a way to support the decision making process of operators. The gap cannot be replaced solely by training but by proper design (Lundh, MacKinnon, & Man, 2015). How can the knowledge gained about adaptive HMI for distributed sociotechnical system contribute to the design of a centralized sociotechnical system, e.g. an alarm management tool for engine control room operators? Can the HMI concept organize the technology to cope with uncertainties and complexities? Can it be adapted to workload and “absorb” human errors and other disturbances so the performance of the overarching system could be improved? Besides, there are a few specific questions about improving transparency of the controlled process through integrated system design:

- How can the underlying cognitive design approach (ecological thinking, SA-oriented design, etc.) be accommodated to characteristics of a centralized sociotechnical system to improve the diagnostic capabilities and individual/team SA?
- How can the cognitive work analysis be employed to the command and control in the integrated system design process of a centralized sociotechnical system?

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